Small-Scale DC Power Plants Supported by Blockchain, AI, and IoT Models: a Faster Transition to Sustainability

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, *Antonio Pereira dos Santos* declare that this thesis, is submitted in fulfilment of the requirements for the award of *[Doctor of Philosophy]*, in the *Faculty of Engineering and IT – FEIT* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

The electricity industry has become the major greenhouse gas (GHG) emitter on Earth since every economic activity relies on it. Wealthy nations headquarter the largest transnational corporations, and to remain competitive, they are compelled to stimulate higher consumption levels, and higher productivity at lower costs. How can global GHG emissions be reduced when political economy and law keep rewarding institutions that directly or not, contributes to the release of emissions? How to reduce emissions when technology has mostly been used to magnify production, and boost indiscriminate consumption?

The transition to renewable energy sources and carbon offset have been the flagship strategies to lower emissions, sponsored by the United Nations, and eagerly adopted by affluent nations. Conversely, the assumption that an eventual transitioning to renewable sources in a localized region, could yield any substantial contribution to climate change in a global scale is rather weak-willed. It may provide a palliative comfort for the wealthy nations to mask environmental liabilities. However, it fails on addressing the emissions' root causes, allowing the perpetuation of the problem.

This research addresses the emissions dilemma within the electricity industry. It features an in-depth study on global emissions, covering causes, sources, drivers, root causes, and providing specifics why present mitigation strategies have failed. Then, it introduces the ADCx model, a small-scale autonomous DC power plant aiming to provide an alternative root for consumers to become sustainable, away from the large-centralised-polluted AC grid. It prioritises cleaner transformation methods and autonomy, irrespective of the type of power sources. Next, it proposes the BAIoT system, where Blockchain, Artificial Intelligence and IoT work together to provide additional features to the ADCx. While ADCx focuses on the network infrastructure, BAIoT builds upon user re-education, network intelligence, rationalising energy consumption, energy trading, and leveraging power demand and supply.

Next, it presents the BAIoTAG framework that establishes the 12 fundamental principles leading to sustainability. It has been strategically conceived to cause minimal impact on the existing AC system, reducing legal barriers, and facilitating cross-country replications. Rather waiting for an effective solution from government, this framework enables citizens to spearhead a local solution, and the formation of off-grid communities.

Lastly, this study presents a comparative case study showing how AI/ML can support small-scale power plants in reaching sustainability. The greater the data granularity, the larger the opportunities for superior predictions, maximise network performance and increasing users' awareness on their local emissions.

Key Index Terms:
DC power plants, microgrid, nanogrid, picogrid, Blockchain, IoT, AI, sustainability

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Publications Associated with this Dissertation

(1) Blockchain: Status quo, enablers and inhibitors: IEEE, 2018, 26th International Conference on Systems Engineering, Sydney, Australia

(2) Greenhouse Gases (GHG) Emissions: Understanding Causes, Sources, Drivers, and Root Causes *(Paper ready to be published)*

(3) Autonomous DC Picogrids, Nanogrids and Microgrids (ADCx): A New Approach for Sustainability *(Paper ready to be published)*

(4) Reaching Sustainability Through Blockchain, AI & IoT: The BAIoT model *(Paper ready to be published)*

(5) BAIOTAG Framework: Enabling a Faster Transition to Sustainability *(Paper ready to be published)*

(6) A Comparative Case Study for the deployment of Machine Learning in Picogrid, Nanogrid & Microgrid *(Paper ready to be published)*

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Chapter 1: Introduction

Young people are on the front line of climate change. Technology should work in their support, not against them. Youngsters should have a top priority in the policy-making process; however, they are not entitled to vote, and their representatives seem to have other priorities. Some justify their age as the impeachment factor for their inability to discern top priorities. Research shows otherwise, as youngsters are far more concerned about the environment than adults [1, 2, 3]. The biased educational system, the constraints from the socio-economical model, and the absence of laws to protect the environment have brought the world to its current status. Climate change has several root causes, and education is at the centre.

A high Energy Return of Investment (EROI) enables people to undertake other economic activities [4, 5, 6]. Conversely, a low EROI would require people to spend much more time in labour activities for household chores, commercial and industrial processes, or transportation. The myth of progress was sowed in the Ancient Age, sponsored by religion, germinated in the Middle Ages, flourished in the Enlightenment period and has been propagated to all cultures since then. The scientific, political and technological advances led to an extreme rise in production and consumption. On the myth of progress, [7] argues that "*civilization has moved, is moving, and will move in a desirable direction. Progress is inevitable... Philosophers, men of science and politicians have accepted the idea of the inevitability of progress.*"

Today, the progress of a nation can be measured in several ways: GDP, HDI, life expectation, power generation (TWh) - or the level of greenhouse (GHG) emissions ($MtCO_2$-e). The higher any of these indicators (or indexes), the greater the harm to the planet, with only a few discrepancies (e.g., the Middle Eastern region). Decoupling these parameters is only possible when well-being, human development, and environmental awareness are prioritised instead of mere economic growth [8, 9].

The global emission problem cannot be addressed individually by each country in a top-down fashion. Every attempt has failed, and nothing in the pipeline points in a different direction. Some countries are deploying renewable, but this has little or no association with reducing global emissions. Since total emission levels keep rising, no one has been capable of proving otherwise. A second myth, *transitioning to renewable*, is helping a group of nations create more businesses, buying more time for concerned stakeholders while enabling the global emission problem to worsen.

This research investigates the root causes of emissions released by the electrical sector and then presents a solution capable of overcoming roadblocks and constraints. The primary outcomes include (a) a study detailing causes, drivers, sources, and root causes of emissions; (b) a new model for power systems - the ADCx model; (c) a model for incorporating state-of-the-art technologies – the BAIoT model, which makes use of Blockchain, IoT and Artificial Intelligence; (d) a framework that brings these two models together (ADCx-BAIoT) and at the meantime creates the conditions to a potential transition to an eco-friendly solution for the electrical sector; (e) experiment results for integration of Blockchain and IoT and a comparative case study deploying Machine Learning in Microgrids, Nanogrids and Picogrids.

1.1. THESIS OUTLINE AND KEYWORDS

THESIS:

> ***"It is possible to reduce emissions by deploying <u>small-scale and autonomous</u> <u>DC power plants</u>, supported by <u>Blockchain</u>,*** **AI** ***and <u>IoT models.</u>"***

KEY INDEX TERMS:

DC power plants**,** *microgrid nanogrid*, *picogrid*, Blockchain, AI, IoT.

Small-scale and Autonomous DC power plants

Unlike the robust, resilient, reliable, and centralised AC power grid that covers vast areas with millions of people, small-scale and autonomous DC power plants focus on solving local electricity requirements at a neighbourhood, street-block, or household level. The concept had existed for over a century, even before electricity was first delivered as a utility service. Owing to its electrical characteristics, DC power networks tend to be decentralised and small-scale. The 1880-1890 decade is widely known as the electrification time since most countries adopted electricity as a public utility, exploring it commercially. Over the next century, these networks grew more extensive, integrated, segmented, regulated, and became the current AC power grid.

At the time, socio-political aspects, economic limitations (recession, World War I), and several technical constraints, e.g., there was no power electronics, no transistors, no solid-state transformers. Altogether, led to the selection of the existing AC power grid, which is regarded today as a major source of emissions. Even thou, most of the constraints faced a hundred years ago, no longer exist. Legislation, lobbying, bureaucracy, corporate interest leaves no space for innovation in the giant system implemented. Monopoly, replacement costs, technical complexities, and legislation became roadblocks to introducing a more environmentally-friendly approach. The ADCx model presented in this study is a decentralised infrastructure with autonomous and small power plants, such as the DC microgrids, Nanogrids, and picogrids.

Microgrids:

A *microgrid* refers to a (i) dedicated site facility equipped with power sources, storage systems, and interconnecting devices, (ii) a coverage area serving two or more affiliated *nanogrids*, (iii) a network system integrating communication and power devices under a unified platform, or (iv) a legal organisation such as association or cooperative formed by the network participants across a region. The site must be strategically positioned and large enough to house all the gears for a small-scale power plant and communication devices. Environmental impact analyses (EIA), feasibility studies, and technical, legal, and scheduling considerations will help assess site location, size, coverage area, and how best to support the community.

Nanogrids:

A *nanogrid* refers to a site housing the nanogrid equipment and interconnection gears, a coverage area, a network that integrates several units (e.g., houses) or an organisation, a legal entity formed by neighbours sharing the same street block. A *nanogrid* site does not necessarily require a dedicated physical site; however, it must have enough space for power devices, terminations, communication, and control systems. The *nanogrid* network integrates a collection of *picogrids* under a single electrical, communication and distributed computing platform. The main goal of an autonomous DC *nanogrid* is to support *picogrids* to reach net-zero emission and minimise environmental impact. A *nanogrid* area is restricted to a street block, a multi-unit building or any geographical location with no connection with the public grid. It may serve residential, commercial, and small industrial facilities. The building blocks of a *nanogrid* system include all the *picogrids*, the electrical gears for their interconnection (e.g., cables, terminations, safety devices), communication components, operating system and depending on the power source or storage systems. The *nanogrid* system enables the peers to communicate, exchange private data, trade (or barter) electricity on their own and import or export electricity to other *nanogrids* via a *microgrid* operator. A *nanogrid* requires an operator responsible for keeping the system operating smoothly. The neighbours sharing the same street block can form a *nanogrid* organisation, agree on a consensus, and elect the service provider for an established period.

Picogrids:

A *picogrid* refers to a single site holding all the circuitry for powering appliances, storage systems and power sources. It can be a house, flat, small commercial or factory facility. A *picogrid* site has a sole proprietorship, and its maximum power capacity is limited to a 100 KW system, regardless of urban or rural areas. A femtogrid refers to each circuit terminated in the breaker box. Use categorisation is an essential aspect of the ADCx model for energy savings, monitoring, classification of the appliances and management reasons. The ADCx model suggests the breakdown of a *picogrid* into nine femtogrids, one for each usage category: (a) lighting, (b) food preservation, (c) cooking and water heating, (d) labour-saving and mechanical tools, (e) education, communication, gaming (f) space cooling and heating, (g) hygiene, (h) outdoor entertainment and (j) electric vehicles. The building blocks of a *picogrid* system include several femtogrids, power sources, storage devices, distribution panels, power metering, cabling, earthing, control and communication gears, and safety. Ideally, a *picogrid* should operate autonomously and become echo sustainable. However, these conditions carry technical and financial constraints; therefore, it becomes attractive to have a picogrid interconnected to other peers via a *nanogrid* network. It can improve network resilience, energy trading (or bartering), strengthening community collaboration, sharing learned lessons, and improving habits.

Blockchain:

Blockchain technology can refer to any software application that uses cryptographic models via a Blockchain platform. It is an emerging solution for decentralised data sharing, allowing untrusted parties to share resources and collaborate based on the consensus protocols, an established set of rules. The Blockchain ecosystem comprises thousands of Blockchain networks and various communities, cryptocurrency exchanges, infrastructure services, development & consulting, wallet and custody services, and mining. Blockchain applications extend far beyond cryptocurrencies, such as healthcare, logistics, data provenance and lineage, cybersecurity, personal identity security use cases, fintech, government technology and many more. A Blockchain platform is characterised by a decentralised database that maintains a growing list of transactional data, a distributed computer network referred to as the ‘Blockchain network’, and a consensus protocol. The distributed database, referred to as “the ledger”, is managed through the consensus protocol. The network participants agreed on the consensus, a list of rules and conditions. It establishes how to verify, validate the transactions (or events) and register results in the ledger. Blockchain uses cryptographic methods to ensure data integrity and availability. Key benefits of Blockchain technology include the absence of a central point of management, elimination of a single point of failure, utilisation of open-source software, and complete visibility of the transactional records by all the nodes. The transaction registration is always visible; however, the details may only be accessible to clients holding special privileges (e.g., a token). The consensus protocol determines how the ledger should be accessed and managed. Each machine in the distributed network maintains a copy of the ledger. That prevents a single point of failure, as machine states are replicated across the Peer-To-Peer (P2P) network. Once logged, the information is immutable in the Blockchain.

Within the BAIoT model, Blockchain has five primary purposes: (a) infrastructure for secure communication among peers and subsystems, (b) data access control, (c) payment rail and rewarding schemes, and (d) enabling local economic development and *circular economy*, and (e) issuance of sustainability certification. Information continually flows between multiple systems, subsystems, and users. IoT initiates a group of activities and stores results locally. Next, part of this information may be required elsewhere as input for other agents, e.g., an AI agent performing forecasting tasks. So, there must be a secure communication path between IoT and AI agents to allow continuous data flow. Blockchain enables the IoT and AI agents to interact safely by providing authentication, accessing rights, verification, ensuring provenance and protecting against data tampering. Blockchain can also provide a medium for payment, or a payment rail, enabling the introduction of rewarding mechanisms through a consensus protocol that can either encourage or demotivate users' behaviours.

Artificial Intelligence (AI):

Artificial intelligence refers to any computer-aided system capable of ingesting data, extracting information, perceiving the environment, and taking actions to maximise its chance of problem-solving. The AI field encompasses several sub-domains, each aiming at specific goals and using particular tools and applications. For instance, machine learning (ML) and deep learning (DL) are components of AI. They are all AI algorithms that create expert systems (or agents). For instance, make predictions or classifications. Typical AI-specific applications include computer (or machine) vision, expert systems, natural language processing (NLP), automated speech recognition and AI planning [10]. Sometimes, artificial may refer to a tool for simulating real case applications and helping decision-making. AI requires specialised software (or hardware) for writing and training machine learning algorithms. AI systems ingest large amounts of data, analyse the data for correlations and patterns, use these patterns to classify the data and make predictions, recommendations, and decisions about future states. Within ADCx-BAIoT models, agents using artificial intelligence algorithms harness the data acquired from the IoT platform, distributed via the Blockchain network, and then carry the analytics. It keeps track of the amount of electricity produced, consumed, and stored throughout the day. AI agents can interpret the variations, learn the patterns and critical times, and distinguish a fault, human errors, or just a consumption peak. All these tasks would be humanly impossible to track. Even for a single house, the level of complexity in managing consumption, generation and storage can be very challenging. All happens in near real-time, and most actions can be automated.

Internet of Things (IoT):

IoT refers to the interconnection of multiple devices under a single platform ranging from a giant network with millions of devices down to a single device, like a smartwatch. Depending on the context, it may refer to a tool, a technology, or a network of objects (physical or virtual) integrated through an IoT platform. Individual devices may not even be directly connected to the Internet, making IoT a misnomer. There are many communication protocols to choose from, depending on the IoT application. It could be via Wi-Fi, mobile phone network (3G, 4G, 5G), Zigbee, MQTT, Bluetooth, LoRaWAN, PLC, and many others. IoT publicity has been intense, with predictions pointing to several billions of devices interconnected over the next few years [11, 12, 13], making it difficult to separate hype from facts. IoT has far more exciting features than interconnecting household devices. IoT simplifies communication protocols, eases the integration complexities of different systems, and becomes a key enabler for many other technologies (e.g., Big Data, ML).

Primary tasks addressed by IoT within the BAIoT model include: (a) interconnectivity and integration among several subsystems under a single framework, (b) automation, collecting and processing the data from every subsystem, (c) publishing results in a local database, (d) extract and wrangle data and publish in a Blockchain, (e) act on the data after AI/ML analytics and (f) send & receive data to all users. A user could be an individual, a process, an application, a device, or a machine. These tasks are critical for integrating the Blockchain and AI systems, unifying the entire system and enabling it to work as a single unit. IoT offers an array of tools and applications, which, combined with Blockchain and AI models, enable consumers to save electricity, rationalise consumption, improve habits, and eliminate CO2 emissions.

1.2. BACKGROUND AND MOTIVATION

The rising in the environmental disaster trend [14, 15], global pandemic, and broad economic distress, all facts combined, provide an excellent opportunity for users to rethink electricity consumption and technology misuse. It can be a great opportunity to improve human life in the opposite direction of the status quo- using technology without depleting the planet.

The world population will likely reach 10 billion inhabitants around 2055 [14], whereas the call for change grows stronger. A new mindset is spreading, demanding a better response toward climate change policies [15], and more specific actions in mitigating the risks already caused by the heat-trapping effects of GHG gas emissions. Conversely, governments are pressured to create more jobs and demand, ensuring GDP growth and keeping the industrial sector strong.

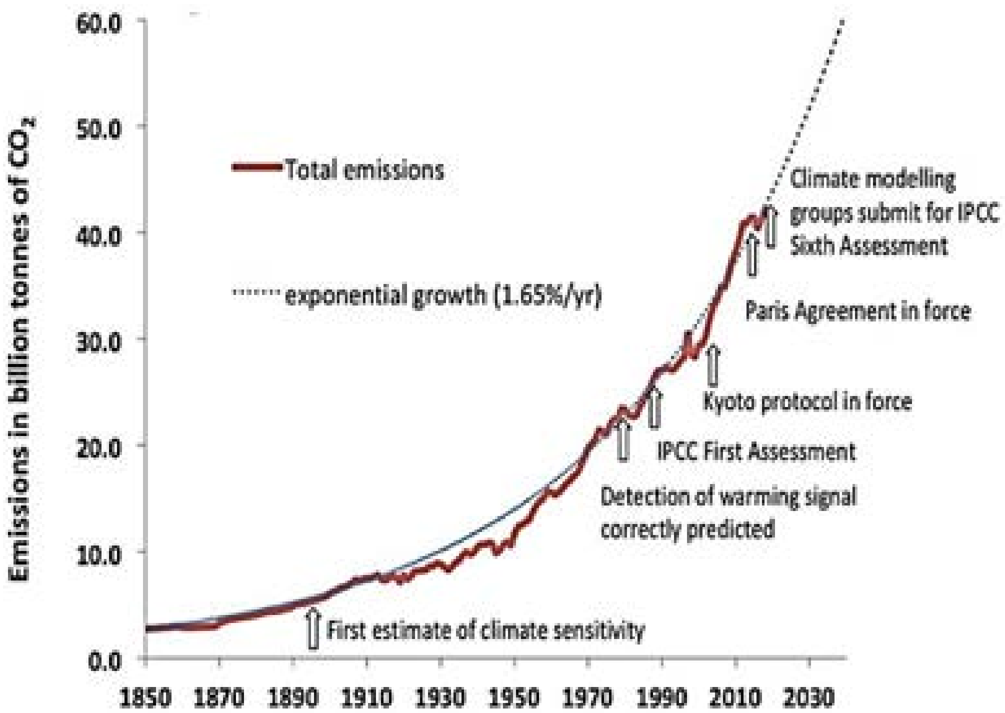
Most powerful transnational corporations today are in the technology, energy, and financial sectors, complementing each other and working in orchestration with governments. The energy sector provides the infrastructure (electricity, fossil fuel), the technology, the stimulation and scale, while the financial provides the lubrication to maintain the status quo. The entire ecosystem is shielded by layers of regulation, sponsored by the government, and founded on monopoly, oligopoly, lobbying, corporatism, and politics. The greater the access to resources, the greater the negotiation and bargaining power with decision-makers. As of Aug 2019, six of the ten most prominent companies by market capitalisation in the USA were in the high-tech and energy domain [16].

Social benefits can only be delivered when the economy runs satisfactorily, whereas the political and economic models only prioritise short-term results. With that background, all the global environmental concerns have been outsourced to the United Nations and their agencies (e.g., UNEP, UNFCC), which in theory, are supposed to implement solutions to reduce emissions and stop climate change. Contrarywise the regulations have been built around establishing the infrastructure so the population can have their basic social needs, e.g., health system, education, security, and infrastructure.

Data aggregators collect transactions' data, exchange it with third parties, and create potential user risks. Sometimes the data comes directly to the client through a sales or licensing agreement, although data aggregators frequently act as agents to enhance the clients' data. Internet media has become infinitely more powerful than traditional channels, such as TV, newspapers, or broadcast. Digital and social media are used as marketing weapons to increase consumption regardless of the consequences to the planet.

Figure 1 shows the exponential growth of carbon dioxide since 1850, exposing the inefficiency of current policies. Analysing this graphic makes it questionable how knowledgeable humans are in using technology. As put by a prominent scientist who showed greater insight, "*should any extra-planetary observer with remote sense capabilities assess the undergoing climate change crisis on Earth, it would be compelled to conclude there is no intelligent life on Earth"* [17]. It is rather peculiar that most current Internet technologies have been used against the planet – and the people. It increases business and creates more demand, but it does not help to improve life quality, no healthier lifestyle. Rather than being used to help people, improve lives,

Figure 1: CO2 Emission from Fossil Fuels and Land



and facilitate living, many digital technologies work towards conditioning people, stimulating action towards consumerism.

Whereas pollution is generated in proportion to the goods produced, consumed, and wasted - the largest institutions are rewarded for stimulating consumption, which translates to more emissions. The public is exposed to methods embedded in social media and searching engines, which increases dependence and leads to negative behaviours.

The idea of long-lasting corporations and personhood is rooted in guilds in the Ancient Ages, which later led to the creation of the joint-stock concept, most notably the East India Company in the early seventeenth century. The Industrial Revolution led to technological innovations, mass production, and developments in transportation, communication, and the emergence of markets for goods. Since then, companies have grown in scale, and the scope and business have increased significantly. Whereas corporations are the driving forces of the economy, the interdependence between government and institutions has grown stronger.

The private sector generates up to 90 per cent of the jobs in developed countries, counting for 60 per cent of all investments and providing more than 80 per cent of government revenues [18]. The government provides the legal mechanisms to support the corporations – and in exchange, corporations employ millions, and demand is automatically increased. The offshoot is global emissions, leading to climate change. The trend in global ecological disasters grew from 5 to over 400 per year over the last 100 years [19, 20]. Droughts, wildfires, heatwaves, insect outbreaks, shrinking ice sheets, and glacial retreat are some side effects.

Remarkably, the academic literature does not distinguish between causes, sources, drivers, and root causes of emissions. Society expected the high educational segment to be a lighthouse for guidance and solving the global warming problem by presenting new models and solutions. The academic community assumed inconsistent positions in the environmental domain [17]. On the one hand, it raises technical skills for graduates while ensuring very low awareness of the environmental consequences. It supports the industry by providing training and solving the staffing problem, a major bottleneck. They are rewarded by the industry, government, and consumers (students) who expect to get a job after graduation. In a way, the high educational sector profits from emissions as any other intermediary business. They are not characterised by the emissions released by themselves; however, by their contribution to other parties in making the problem worse. The majority of the labour force (~71%) is linked to the production chain since the service sector is a subsidiary of the industrial sector [21, 22] – which has become the market niche for the higher education segment.

The electrical sector remains highly controlled by the state and impacted by the legislation. Electricity must be generated at the lowest costs to decrease industrial production costs. With many key performance indicators to be met, pressure, and risks, power producers are indirectly forced to deploy unclean methods – so lower prices can be delivered – at the expense of the environment and future generations. The system is unsustainable since industries continually increase production, driving consumers to spend more electricity. Finding the right balance requires many compromises on every front, society, corporations, and government. There are conflicting interests, constraints, and many roadblocks. When concealed interests, lobbies, and national strategies are factored in, individual governments have limited options to propose law changes to solve the GHG emission problem. Good ideas are turned into stillborn projects or adapted to satisfy the current stakeholders, leading to the perpetuation of the emissions problem.

The idea of transitioning to renewable sources, together with the carbon trade strategy, without a sound plan involving the user and other stakeholders, is leading to the continuation of the problem in the electrical sector. Finding a solution away from the current model becomes vital to solving the global emission problem, which is the core of this study.

1.2.1. On Business, Technologies & Human Factors

When individuals progress on the socio-economic ladder, the consumption rates tend to increase similarly. Governments' primary mission is to provide the infrastructure so that demand can be created, the business can grow, and benefits can be delivered to the population. If there is no business, there are no vendors, corporations, jobs, and government. Price competition induces lower costs which in turn leads to unclean solutions.

Fossil fuels have been part of human development and present in every major technological breakthrough since the metal age. That is explainable by its abundance (low cost) and high energy density. Every manufactured product has a connection with fossil fuel burning, e.g., metals, glasses, plastic, cement, power generation, rail transportation, automobile, aircraft, telephone, computer hardware and software. Even the agriculture sector heavily relies on fossil fuels, and large-scale grain production would halt without fertilizers, transportation and commercialisation.

International price competition has been present in human history since the inception of money, which led the world to the current mapping geo configuration. A nation is likely to cease or be forced to merge with other countries if not capable of offering price competitiveness for its products. Fossil fuel is foundational for international price competitiveness since it drives energy prices, directly impacting production costs. Fossil fuel, energy, and price competition are part of human history and evolution, and nothing can debate these foundational realities.

Corporations create the products and generate employment; people create demand, government get their cut, and everything else follows suit. Governments rely on business as much as corporations need consumers with high acquisition power; otherwise, both cease to exist. The greater the motivation for individuals to acquire new products and services, the better for governments and corporations, regardless if they fulfil needs, desires, or pure money (or time) wasting.

Lowering global GHG emissions requires changes in industrial transformation methods, user re-education on consumption habits, tools, mechanisms, and new infrastructure. New values, parameters, and tools must exist that enable users to understand and raise awareness of their participation in the emission chain. When users acquire a product (or consume electricity), they also trigger a remote corporation to produce emissions on their behalf. Corporations deploy media channels efficiently to influence, hook, and trigger users to keep consuming indefinitely. Until the consumers realise they can reverse this trend, emissions will likely keep rising.

1.2.2. On the Impact of Fossil Fuel Prices on Cleaner Methods for Power Generation

Fossil fuel feedstock (coal, petroleum, oil, natural gas) prices directly impact the economic viability of cleaner electricity generation. Since lowering electricity prices is mandatory to achieve global market competitiveness and rising GDP, when fossil fuel is cheap, it makes it even harder to find a competitive price solution. So, by manipulating fossil fuel prices, governments and the upper stream energy sector can control the deployment rate of renewable sources.

Considering the absence of effective regulation, the fiscal incentives received from governments to lower generation costs, and the international price competition, the deployment of low-cost methods in the combustion of fossil fuels has become the natural choice for electricity producers. So, a small group of stakeholders controlling fossil fuel prices influences the amount of CO2 emissions. So, on the one hand, lowering fossil fuel prices demotivate the deployment of renewables. Conversely, it motivates the increase in consumption by the user and the acquisition of new devices.

While a small portion of stakeholders shows legitimate concerns about lowering global emissions and understand the high costs and risks in the long term, the majority have very different short-term goals. Most stakeholders in the political and financial spaces are judged exclusively by their short-term results - some take advantage of the situation by lobbying to lower electricity prices, others by silencing. Power brokers can swiftly shuffle strategies, hiding behind bureaucracy while CO_2 emissions rise. Low energy prices benefit everyone, except the environment and future generations.

1.2.3. On Regulation Gaps and Roadblocks

Past decisions on the electricity segment significantly contributed to the current environmental crisis. The regulation led to monopoly and oligopoly systems, including service providers and international alliances. Only a few stakeholders have the power to make decisions that affect the whole planet. The problem gains a new level of complexity as most key stakeholders have diversified investments. Some stakeholders may not be directly involved in the emissions themselves, but their short-term interests outweigh environmental concerns, for instance, the financiers, lobbyists, silent investors, and the like.

Electrification started at the end of the 19th century when incandescent lighting and motors were the only applications. Today, there are hundreds of application types. Incandescent lights became a rarity. Business and political priorities negatively influenced technical decisions [23]. With the power network expansion, around 1920-1930, regulations mainly were focused on integrating different systems, creating a national grid, protection, performance indicators, and load balancing – apart from lowering prices.

Moreover, there was warfare and a strong drive for fast economic recovery. The result was a severely compromised regulation favouring large, centralised, fossil fuel-based power plants. Technical and legal complexities, high level of investment, uncertainties, monopoly, all these factors combined left no room for environmentally friendly solutions or new players.

Technical and commercial complexities, intertwined regulations, and internal and external dependencies led to the existing power infrastructure. Law and regulation have become a major roadblock to introducing cleaner electricity solutions. Electricity restructuring touches on the interests of almost every primary economic sector, from households to heavy industry. Through the years, key stakeholders in the electricity industry have learned how to protect the laws from changes and jeopardise the environment. Many attempts have been tried, including deregulation, privatisation, and liberalisation; however, emissions keep rising as usual as if no actions had ever taken place.

Mitigating climate changes heavily relies on raising environmental awareness so users can learn new habits and force policymakers to adopt new paths toward cleaner transformation methods. The lower the population awareness concerning climate change and electricity production, the easier for current brokers to maintain the status quo. Policymakers have not factored in the long-term effects on the environment and the rights of future generations. There is no legislation enforcing electricity producers to deploy cleaner methods. Conversely, trade competition, the economy of scale, and lower prices policies force electricity producers to deploy minimal cost methods, which translates to releasing tons of GHG emissions daily into the atmosphere. While the public remains unaware of the many steps and the huge volumes of carbon and methane emissions involved in producing electricity, the emission trend continues to rise.

Large, centralised, supported by emission-intensive production methods versus small-scale, decentralised using cleaner methods lie on the opposite side in the strategic design scale. So, any feasibility study that compares these two contrasting approaches, considering only the short-term economics, becomes biased from the start. A fair comparison would only be possible when design goals are alike. Centralised and large power plants become cost-effective in the short term because it deploys polluted methods – and does not take into account the economics in the long run. The trend in global ecological disasters grew from 5 to over 400 per year over the last 100 years [19, 20]. Only in the USA, the total cost of 323 events over the last 40 years exceeds $2.195 trillion [24], representing a fraction of the global costs. The estimated yearly costs for global environmental catastrophes are around $1.7 trillion. According to a global survey in 2021, over 730 economists find that the benefits of action preventively far outweigh these costs [25].

On the other hand, power brokers and financiers regard the net present value and the short-term risks vs benefits over the next few decades – until they ensure their investment return. As previously mentioned, there is no law enforcement, no legal instrument, enforcing decision-makers to factor in long-term environmental risks – and associated damages caused on a global scale.

Many stochastic variables surround the energy sector, such as international oil prices, offer and demand, local market price policies, lasseiz-faire, and price manipulation by cartels. The electrical sector is strongly centralised, controlled by the state, deeply influenced by oil and gas price national policies, and indirectly by giant transnational corporations (oil & gas lobbies). It is highly regulated and enveloped with conservatism. As a result, if the same rules, metrics, and stakeholders are maintained, the GHG emission problem will likely worsen.

Apart from emissions, other side effects of the current legislations are (a) the existing long-distance AC transmission lines and network infrastructure have very little use in a fully decentralised, low-carbon design approach, (b) the existing infrastructure turned into an extra barrier against innovative approaches since the latter would be forced to comply with the older system, increasing initial costs and killing the motivation (for innovation) at the cradle (c) the existing stakeholders have nothing to gain by introducing more competitors. If maintained the same power infrastructure, the same core regulation, regulators, and the same eco-system followed by ineffective colourful, however ineffective adjustments, the legislation gap will likely remain the same – so the emissions trend.

The strong correlation between per capita energy consumption, CO_2 emissions, and the social development index is widely accepted [8, 26]. Decoupling these trends may only be possible if policy instruments are radically changed. It is not logical to assert that a few developed nations successfully lowering their per-capita emissions within their territory will trigger other nations to follow suit on a global scale. Country sizes, population density, IDH, social inequality, location, economic stability, and dozens of other factors must be factored in on a case-by-case basis.

The increase of GDP through the stimulation of production and consumption, and the lower energy prices, have led to regulations replicated worldwide. This recipe took place in Western Europe, North America and more recently in parts of Asia. It would be tough to convince developing countries to adopt eco-friendly policies since all developed countries have benefitted from low-cost models at the expense of the environment. There is a strong possibility that developing nations will repeat the same formula.

The legislation vacuum to protect the environment make individuals and communities powerless to try new approaches. A clean power plant design approach requires sustainability-driven innovation and lower consumption through education to improve user habits. Changing national legislation to create a positive global impact on the environment is a highly optimistic goal. A more realistic goal would require a bottom-up approach, including the individuals and the communities, and then reaching out to institutions and governments.

1.2.4. On The Transitioning from Fossil Fuel to Renewable Sources

Deploying renewable sources does not necessarily imply being environmentally neutral, whereas fossil fuel does not necessarily imply being environmentally hostile or “dirty”. Every object, facility, or service has a carbon footprint. As long as all environmental effects are mitigated adequately, any power source, renewable or not, can be useful. It all depends on the circumstances, availability, location, and willingness of the population and power brokers.

Being renewable is neither a guarantee of being sustainable nor reliable, so grouping all the renewable solutions under a single package can be risky. Each renewable source causes an environmental impact – each solution brings a package of outcomes with specific attributes, carrying different emission payback time (EPBT). The scaling factor can also provide new perspectives. Ethanol (alcohol) is often regarded as a renewable source and can be obtained from biomass such as sugarcane, corn, or other crops. However, razing pristine lands to grow sugarcane plantations or burning practices before harvesting to facilitate the reaping and reducing costs are emissions-intensive. The industrial transformation methods from sugar cane, milling, fermentation, crystallisation, and transportation are very energy-intensive, with high GHG emissions. Crop plantations require vast amounts of fertilizers, pesticides and herbicides that kill birds and ultimately ends on rivers, also killing fishes. So, alcohol is a renewable fuel, but all the transformation processes running in the background are far from environmentally friendly.

Large hydropower plants may inundate huge areas and disrupt wildlife habitats. It can create enormous environmental impact and social instability; in some cases, decimating fish species and may force the relocation of vulnerable communities; Besides, it uses a massive amount of concrete and steel, which are highly emission-intensive. The large-scale onshore wind farm is another debatable example of renewables. The environmental impact of wind power is immediate, starting with the construction, which is very energy and resource-intensive, causing a direct impact on local biomes. A few studies have indicated that if the GHG budget is calculated on a short-mid-term basis (e.g., ten years), wind farms can cause more climate impact than coal or natural gas.

On the other hand, if a long-term perspective is taken (e.g., 1 thousand years), wind power would have considerably less GHG emissions than coal or gas [27, 28, 29].

Despite uranium not being a renewable source, some stakeholders still refer to nuclear power as a renewable source. It has lower carbon emissions during operations and is scalable. Reliability versus liabilities can be debatable. When accidents happen, biomes can be decimated in a short period, and the environmental impact lasts for centuries, affecting the present and future generations. Like wind power, nuclear plants have a very low carbon footprint during operations. However, construction, decommissioning, disposal, and waste management can be highly emission-intensive.

Even photovoltaic solar systems cannot be regarded as entirely environmentally neutral. A few rooftop solar panels can be perceived as neutral to the environment (although it is not). Nevertheless, several millions of panels in a single solar park requiring continuous wet cooling using freshwater is a very different scenario. It uses glasses, metallurgical grade silicon (or thin-film), aluminium, rare-earth elements, and steel frames, all energy-intensive, and their production does cause environmental impact. While the power conversion process from solar to electricity does not involve CO2 emissions, there are many other concerns regarding large-scale deployment. The "lake effect" can lead to the killing of birds due to its large reflective area. The manufacturing and disposal processes involve several toxic materials, which, if not handled properly, pose serious environmental and public health concerns [30, 31].

Many countries have announced policies and pledges to reach net-zero emission by 2050 becomes. However, even in the best-case scenario, where promises become a reality, the final impact on global emissions may be negligible. Developed countries may account for 13% (1.026 Billion) of the world population, whereas the global population is estimated to reach 10 billion around 2055. The extra 2 billion people are likely to cause a much greater impact on the planet than any optimistic promise of transition to renewables. Besides, as developing nations move up the socio-economic ladder, their production and consumption, waste, and emissions must increase.

Motivating householders to deploy solar panels without a re-education program to reduce acquisitions and lower consumption has been ineffective in mitigating the global emissions problem. The rebound effect from the economic saving may trigger new behaviours leading to the same amount of emissions. The rebound effect has been intensively explored in the literature [32, 33].

Moreover, the duck curve problem [34] refers to an excess of solar power availability during the day and a power shortage during peak hours. Again, the householder may think that exporting electricity to the grid will contribute to the overall reduction of power produced by the operator, which may be a very different reality. The reality is that global emissions keep rising, which yields questioning about whether rooftop solar has ever been effective in lowering global emissions. Lowering electricity bills and lowering global emissions are separate dilemmas that can be easily confused, which helps the overall maintenance of the status quo.

It turns out that solar power solutions' efficiency in supporting the householder seems unquestionable; however, its efficiency in contributing to lower global emissions has been highly questionable. There may be some inefficiency in the power grid, e.g., power conversions, storage, and transmission losses. This can help explain why global emission keeps rising when millions of householders are now deploying rooftops [35].

Fossil fuel has often been labelled “dirty”, ecologically unfriendly, and beset by limited supply. These are often justifications for the adoption of renewables, and there are notorious misconceptions about these reasonings. Hydrocarbon matter is a natural resource, like water, wind, or sun, so the renewability aspect is a mere question of perspectives explored by marketers. The current methods for extracting, refining, and processing fossil fuels are environmentally unfriendly — as it can be highly costly to install filters, capture, or sequestrate CO2 to avoid dispersion. So, it implies that “dirty” are attributes of the processes and not from the fossil matter.

Whereas the upstream energy sector carries the burden of improving extraction and processing methods, the extra costs impact every economic sector, which dashes government interests. Since the state is the de-facto manager of the electricity industry, damage control must be in place. That is where the notion of renewable sources comes in handy. Whereas renewable sources have been projected to the public as the greatest solution to solve the emission problem, they are also allowing the industries to carry on business as usual. While stakeholders broadcast the *transitioning to renewables* as the remedy for solving the climate problem and entertaining the population with solar and wind power, the emission problem is getting worse.

The methods deployed for mining coal (and ores) and extracting oil and gases affect electricity prices and every other stakeholder, such as financers, government, industry and householders. Whereas there is no efficient legislation to protect the environment, the method with minimum cost is the preferred choice – which explains why GHG emissions are high. Hydrocarbon is also required for other industrial applications, such as in heavy industries (e.g., steel, iron, copper). Crude oil has more than 6,000 by-products (e.g., plastic, kerosene, diesel, gasoline, shampoo, paint, nylons, cosmetics, asphalt, ammonia). Thus, fossil fuels are not replaceable in industrial applications – only methods can be improved.

Fossil fuel reserves have had a history of poor predictions, and the bell-shaped forecasting curves proposed by geologists in the 1950s have never materialised [36]. Many studies predicting the end of the cheap-oil era, the Armageddon, have been proved “wrong” [37, 38]. Technology continually changes, and new methods lead to more productivity and access to what was considered impossible in the past. What was not economically viable ten years ago and underestimated may become the ideal scenario a few decades later. Some authors even suggest “*we have far too much oil, gas, natural gas and coal - not too little*” [39].

Figure 2 shows the distribution of proven reserves from BP for 1999, 2009 and 2019, respectively [40]. The oil prices may be the best metrics for indicating the level of scarcity and oversupply—low prices imply a low risk of shortage (up to a certain extent) and vice-versa. Rising oil prices motivate the deployment of renewables – and vice versa. Betting the fossil fuel depletion scenario as the main justification for

Figure 2: *Distribution of proved fossil fuel reserves in percentages – Source BP (2020)*

renewable sources is a very fragile and risky assumption [41]. Echoing the words of a former Saudi Arabian Oil Minister, "*the Stone Age came to an end, not because we had a lack of stones, and the oil age will end not because we have a lack of oil*" [36, 42].

There have been many new approaches to mitigate the GHG emissions of fossil fuel deployment [43]. Carbon capture and storage (CCS), carbon capture and utilisation (CCU), and carbon sequestration are some approaches under consideration. CCS refers to capturing CO2 before it enters the atmosphere and storing it underground for a very long term. The concept can be applied to any industrial plant, e.g., oil refineries, cement kilns, iron foundries, flare stacks, and others. CCU extends the reach of the CCS approach by adding a utilisation factor, creating a value-added product for the CO2 captured, e.g., plastic, fertilizers, hydrogen, and many others [44]. Carbon sequestration (CS) refers to the long-term removal, capture, or sequestration of CO2 from the atmosphere to slow or reverse atmospheric pollution problems. It can be terrestrial and geological sequestration. Biological sequestration may involve reforestation, afforestation, creation of sustainable forests, genetic engineering, peatlands (peat bogs), and enhancing carbon removal. Although there is no shortage of ideas, all these solutions have associated costs that must be factored in and fit into the business models.

The critical points on this topic are: (1) the notion of renewable sources being environmentally neutral and the idea that fossil fuel is the root cause of the environmental disarray are both grossly misconceived; (2) In order to assess the environmental impact of any solution, the entire life cycle, cradle to grave, must be taken into consideration; (3) the processes for extracting, transforming, and handling fossil fuels must include provisions for eliminating GHG emissions; (4) Fossil fuel reserves are not being depleted, on the contrary, with newer technologies, new reserves can be found; (5) There are several ways to capture the GHG emissions before reaching the atmosphere -as there are ways to sequestrated and mitigate the CO2 emissions already emitted, and the associated costs must be factored in the new business models; (6) The idea of fully transitioning from fossil fuel to renewable sources by 2050 is doubtful, with many loopholes, and prolongs the problem, rather than providing an efficient solution.

1.2.5. On Eco-Efficiency, Life Cycle Assessment and Environmental Impact Assessment

Ecology is one of the several domains in biology concerning the relationship between organisms and the surrounding environment. The term overlaps with biogeography, evolutionary biology, genetics, ethology, and natural history. Efficiency deals with the rate of achievement or performance on achieving a particular condition given one or more inputs, thus usually applicable to energy systems, machines, processes, situations, materials, operations, or procedures. Quantifying the impact of an object, process, or physical entity (e.g., a manufacturing plant) in terms of environmental efficiency is not a straightforward task.

The term eco-efficiency has been loosely applied by scholars and institutions, mostly in the economic context. The World Business Council for Sustainable Development (WBCSD) 1992 introduced the concept of eco-efficiency as an approach to capture the notion of producing more results (desirable) with fewer resources and causing the minimum ecological impact (undesirable) [45] - or the ratio of economic output to environmental input. Various interpretations are possible, given the diversity of companies and goals [46]. Some scholars have even gone further to use public data from the OECD countries and determine the eco-efficiency of an entire country based on electricity consumption, carbon emission, and sales. Then, mathematical models were applied, data envelopment analyses (DEA) decision-making units (DMU) and the results established that a group of countries were eco-efficient while others were not [47].

Labelling an entire country, a region, a cluster of industries or even a single business as eco-efficient (or not) through generic approaches can be misleading and give rise to adverse effects. In a chain reaction, constrained assessments can trigger disastrous decisions, leading the problem to worsen. It is not logical to assert that a single figure (index) would fairly represent the impact in nature in any meaningful way [48]. The harmonisation of the term eco-efficiency has been tried across several international standards [49]. In short, the greater the generalisations, the lesser the precision, and the higher the chances of biases.

Life cycle assessment (LCA), sometimes referred to as life cycle analysis, is another approach to evaluating environmental impact. The LCA is a general framework conceived around the 1960s to analyze packaging alternatives and other bulk commodities when environmental degradation became a major concern. Later, the concept of LCA expanded to include services and processes. More recently, two major LCA standards replaced all the previous standards. The ISO 14040 series define the principles and framework for LCA, including goal & scope, inventory analyses, interpretations, impact assessment, and technical report [50], and ISO 14044 outlines the requirements and guidelines [51]. However, these standards are only intended for comparative assertion purposes, a holistic approach to specific scenarios. For instance, is '*option A'* more environmentally friendly than '*option B'?* Or should a component be used instead of another to minimize the environmental impact? The object studied in LCA can be a physical product, a manufactured object, an industrial unit, an organisation, a cluster of institutions, or applied to an entire region [52]. The term "product system" indicates a life cycle perspective for a given product consisting of the set of processes, interlinked units, and fluxes that model the product life cycle.

While eco-efficiency is attached to a business perspective, the LCA tends to be associated with the production processes. The goal is gathering data, building a case, listing an inventory including every possible stage, and then creating a comparative framework. The LCA results shall provide insights to decision-makers on where to improve processes or modify components to reduce environmental impact. However, LCA standards have flaws and attract criticism [53]. LCA has no utility if the underlying physical data is poor. Field experience to identify each stage of an end-to-end production stage and be supported by subject matter experts in each subfield are key [54]. Collecting data from observations, calculations, and the inclusion (or absence) of data from external suppliers can substantially impact results. Disconsidering external data may make it easier to reach a result, but it may also compromise the entire LCA purpose.

Simplification is necessary, but over-simplification in modelling can be disastrous to the environment. The difference with modelling in other fields is that there is no easy way to monitor results. Organisations can now count on third-party services to verify results, which introduces other risks, e.g., greenwashing. Decades later, a misconducted LCA may become transparent to the public that the model was wrong, contributing to worsening environmental problems.

LCA complexity increases with the range of unit processes, field domains, inputs, outputs, and conflicting data interpretations. Guidelines covering the same product categories and market domains without adequate adaptation make it hard for the practitioner. E.g., there are varied interpretations of ISO 14044 concerning system boundaries, cut-off rules, unit processes to link to specific inputs, and rules for handling coproducts. Given the ambiguities in interpretations, different practitioners may claim compliance with a certain standard and present conflicting results [55].

Both LCA and eco-efficiency can be useful when specific and contextual comparisons are required. Various software tools are available to support practitioners, although none would replace field expertise in finding the relevant information and making the appropriate decisions. Software tools may only include a few parameters (e.g., power, emissions, waste), disregard many other relevant inputs, and provide partial or misleading results. For instance, an LCA may include only one type of gas (CO_2), disregard all other gases (CH4, N20, SF6), and claim sustainability without making proper remarks. When components or services are outsourced without accurate data, the LCA may become very limited in scope. Biased LCAs may cover a short scope of a multi-dimensional environmental problem (e.g., emissions) and disregard all other impacts, such as water contamination, bird-killing, and fishing species.

A third approach is to conduct an environmental impact analysis (EIA), a methodology to evaluate a proposed project's environmental consequences regarding positive and negative impacts. The primary purpose is to ensure that decision-makers be concerned about the environmental aspects when choosing whether or not to approve a project. The study, therefore, requires a multidisciplinary approach and feasibility stage of a project. In general, an EIA should include the following steps: screening, scoping, public involvement, impact analyses, mitigation, report, review and decision-making. The impacts may include all relevant aspects of the natural, economic, human, and social environment.

Many countries have legislation enforcing the use of EIA for certain activities. However, organisations can outsource emission-intensive activities to third parties and lowers their local emissions. The International Association for Impact Assessment (IAIA) has over 120 nations participants, organizes forums and conferences and promotes best practices. Depending on size, location, and context, public agents at municipal, state or federal levels impose their policies, and a formal procedure must be followed. It is a legal instrument for environmental management as part of an approval procedure, decision-making, and administrative practices.

In some cases, it may involve public participation through voting, discussions, and a timeline for the public to manifest about the project. Participants may contest or propose mitigation actions, and they may be subject to judicial review. As the focus is local, the global impact in the long term may not be properly assessed. Local certification does not necessarily guarantee the long-term environmental impact on a global scale.

The heaviest industries like cement, iron, steel, aluminium, petrochemicals, and electricity producers are usually located in remote areas where legislations are less restrictive. Given their importance to local governments in job creation, economic contribution, lobbying and interests, the environmental aspects are left on a secondary plan. Environmental impact analyses should not be restricted to new projects in urban areas. If the goal is to cut emissions, every existing polluter must go through the EIA whenever necessary and correct the problem. Besides, the concept of EIA should be extended beyond the physical premises. Any procedure, product, technology, or service that indirectly causes users to consume more electricity, or transportation, should go through an EIA.

The old say “what gets measured gets managed” is a good start, however insufficient. Quantitative sustainability assessment demands in-depth skills, time and cost investment. Any organisation that relies on any form of energy or natural resources profits from emissions, directly or not. Most (if not all) of these institutions have no interest in displaying their deficiencies or participation in the destruction chain to the public, so they may use EIA, LCA or eco-efficiency studies to cover up their footpaths.

This study has not identified any tool, procedure, or credible framework allowing a throughout assessment of the environmental impact caused for the most traditional polluting industries. A comprehensive impact inventory must account for potential risks to humans in all categories, species and organisms and their biomes, biodiversity, and intensity, comprising all domains, aquatic, terrestrial, and aerial—especially future generations, the children, indigenous communities, and particular communities. If any of these components are left out, it may become biased or a meaningless exercise.

The EIA, LCA or eco-efficiency studies are all predictive undertakings at their core. They all rely on the ability of who is conducting the study. The standards have some degree of importance but are not a replacement for experience. As in many other fields, certifications have become another market niche to satisfy local compliance, creating business opportunities for local stakeholders. That may help explain why GHG emissions keep rising, as is deforestation and many other negative environmental practices.

1.2.6. On The Impact of Global Value Chain – GVC

Global value chain (GVC) refers to the fragmentation of the production process across countries. A bike design may be conceptualised in Italy, prototyped in China, assembled in Vietnam with components from a dozen countries, shipped to a retailer in India, and sold on an e-commerce platform to a customer in the UK. A more complex product, e.g., a mobile phone, may have hundreds of processes and thousands of suppliers worldwide. Quantifying the environmental impact of products with multiple suppliers becomes a highly complex undertaking. GVC is an aftermath of industrialization, mobility, price competition, high speed communication, which ultimately impacts on the sustainability of the planet (Figure 3).

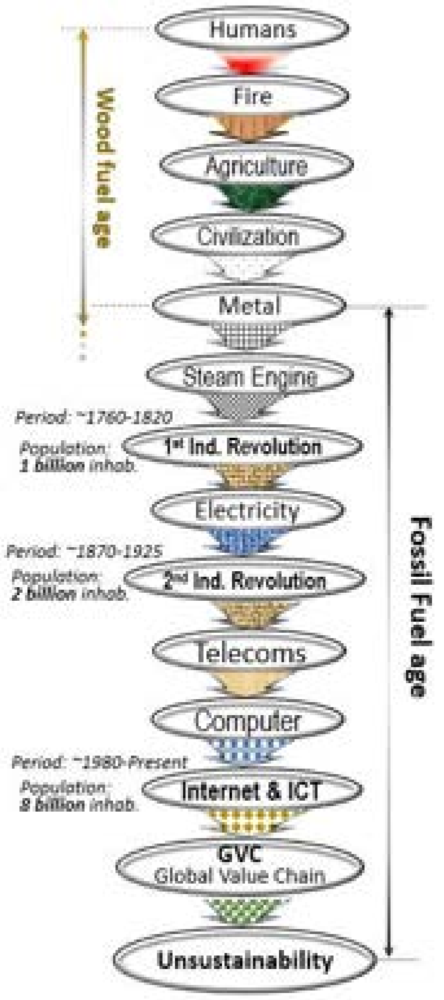


Figure 3: Global Value Chain link to unsustainability

The world container ship industry grew from 11 DWT (deadweight tonnage) in 1981 to 282 DWT in 2021, involving 98,140 vessels and 23 million containers (twenty-foot equivalent) worldwide [56, 57]. It is estimated that 3 to 5 million containers cross oceans daily. Many thousands fall into the ocean yearly, harming wild like, and crushing aquatic habitats [58]. Sulfuric acid, oil spills, nitride acid, debris, and accidents are widespread – and the media only report a small fraction of the total disasters.

The Internet and Information & Communications Technologies (ICT) have spurred the rise of GVC, and international trades have been growing steadily. Automation in industrialised countries has boosted importing from initially commodity-based supplying countries. GVC trade today represents nearly 50% share of the total trades on the planet [59]. Developing economies are growing faster, poverty is falling sharply, and consumption is growing steadily (e.g., China, India, Bangladesh, Philippines, Vietnam, etc.). On the other hand, technological development has brought several adverse environmental side effects.

GVC improves efficiency and quality and reduces prices – however, it increases the complexities in tracking accountability for global emissions. As emission-intensive tasks can be outsourced overseas, corporations can conceal their direct participation and free ride on global emissions. GVC makes it unfeasible to conduct environmental impact analyses on products assembled in developing markets with thousands of components worldwide [60].

1.3. Research Gap and Research Questions

Whereas electricity producers deploy large and centralised AC design models benefiting from unclean methods to lower costs, monopoly leaves no alternative to householders other than using the public grid. As a result, the AC power system becomes a major roadblock to lowering emissions since it does not allow other players. When the goal is to become environmentally neutral, a system must include the opposite characteristics of the status quo. So, to avoid the monopoly problem, a system must focus on small coverage areas, be autonomous, and decentralised, and aim to reach net-zero locally. To avoid technical conflicts with the AC system and minimise power transmission losses, the new system must preferably run on DC power.

- The first gap found in the literature is the absence of academic literature clarifying the reasons, causes, drivers, and root causes of global emissions that to the current emissions.

- The second gap is the absence of literature proposing small and decentralised DC power systems as an alternative to the existing AC power grid.
- The third gap is the absence of solutions focusing on reducing emissions from the electricity supply and distribution segment.

The associated research questions with these gaps are:

a) What are the root causes of the global emissions problem?

b) How to create an alternative power system capable of competing with the AC grid and, in the meantime, prioritise the environment?

c) How to introduce mechanisms (incentives) to lower emissions and motivate users to migrate to a more sustainable power system?

d) Would it be possible to create a framework capable of overcoming the emissions problem on a global scale?

The above research questions gave rise to two models and a framework: ADCx, BAIoT and BAIoTAG. The acronym ADCx stands for Autonomous DC power grids, where the ‘x’ can refer to *picogrids*, *nanogrids* and *microgrids*. The BAIoT model comprises Blockchain, AI, and IoT to add intelligence to enable trustable communication, payment rail and analytics among peers. The BAIoTAG framework envelops the ADCx and BAIoT models. It provides the foundation for the ADCx and BAIoT models while allowing the inclusion of theoretical games to further motivate users towards reaching echo sustainability. The BAIoTAG is unique in creating the necessary environment to overcome the emissions problem from the electrical sector.

Another gap found in the literature is the absence of any studies combining all these components: (a) autonomous and small-scale power plants (e.g., *microgrids*, *nanogrids, picogrids*), (b) DC distribution power systems, (c) Blockchain technology, (d) artificial intelligence, and (e) sustainability.

1.4. RESEARCH OBJECTIVES

The specifics, timely bound, and attainable objectives for this research include:

Objective 1: Identify sources, drivers, causes and potential root causes of global GHG emissions from the electricity industry.

Objective 2: Present an alternative model to the existing power utility system allowing consumers to interconnect through small and autonomous DC power plants.

Objective 3: Present a conceptual model showing how Blockchain, AI and IoT can support small-scale power plants to reach sustainability locally.

Objective 4: Create a framework for the power utility system supporting a faster transition to sustainability.

Objective 5: Create a comparison case study for small-scale power plants (*microgrids*, *nanogrids* and *picogrids)* demonstrating how Machine Learning models can make predictions with an accuracy of over 90% for one day ahead of power consumption.

1.5. RESEARCH AIMS (from the stakeholders' sight)

The research aims and expectations from the stakeholders' point of view include:

i) Explore root causes for anthropogenic GHG emissions caused by the electricity industry.

ii) Based on the above (a), create a solution capable of overcoming the major roadblocks that could lead to a faster transition to sustainability.

iii) Provide a roadmap on how the state-of-the-art technologies can enable users to reach a net-zero carbon footprint.

iv) Establish how accurate machine learning (ML) models can learn and make predictions for power consumption in *picogrids*, *nanogrids* and *microgrid*s.

1.6. OVERALL METHODOLOGY AND RESEARCH METHODS

The research methodology is presented in two modalities, (a) an exploratory approach for identifying potential root causes for emissions, which lays the foundation for the proposition for a framework to overcome the mitigate the problem and enable consumers to reach net-zero emissions; (b) a model-based systems engineering (MBSE) to identify systems requirements, design, analysis, leading to the conceptual design; (c) a comparative case study, which makes use of consumption data on a time series format enabled by machine learning models so that conclusions can be made about the predictability aspects for *microgrids*, *nanogrids* and *picogrids*. Prediction is a foundational requirement for the BAIoT-ADCx models since autonomy and sustainability are the key goals. The overall methodologies are explored in Chapter 3 of this research.

1.7. RESEARCH SIGNIFICANCE & CONTRIBUTIONS

On 14 February 2022, Mauna Loa Observatory registered 421.59 ppm (parts per million), the highest-ever recorded CO2 emission level in human history [61], implying that all attempts to mitigate global GHG emissions over the last century have failed. The alerts and recommendations for policymakers under the IPCC's Fifth (AR5) report in 2014 have been misunderstood, disregarded, or miscalculated [62]. GHG emissions involve many domains, far beyond the physical science domain, such as the economic model, human factor, business, political system, and many others.

Climate change is a real threat, and ecological disasters intensify yearly [19, 20]. Thus, global emissions remain an ongoing and complex problem to be solved. Thus, this research brings the following unique contributions to the electricity industry field:

a. Provides a comprehensive study of the global emissions' causes, sources, drivers, and root causes which has no parallel in the literature.

b. Promotes the education of researchers, students, and the general public on the many ramifications of global emissions, enabling the distinction between publicity and facts, conflicts of interest, clarifying misunderstandings and filling knowledge gaps.

c. Introduces a new approach for reaching net-zero from a bottom-up approach. The ADCx model offers a new pathway for householders to reach net-zero emissions in their premises or neighbourhoods without relying on governments.

d. Proposes BAIoT as an enabling supporting system for small-scale decentralised power grids, adding unique capabilities to ADCx, such as analytics, intelligence, and automation. BAIoT brings together several concepts scattered in the literature (Blockchain, AI, IoT).

e. Introduces an end-to-end framework that considers the root causes of emissions – conceived to minimize the dependence on government, political actors, and legislation changes.

f. Proposes the BAIoTAG framework, which provides the big picture on how small-scale can add many positive outcomes to the community beyond the electricity space. E.g., Local Economic Development (LED) and *circular economy*.

g. Introduces mechanisms for users to take control of their carbon footprints, control their consumption and educate themselves on the importance of zero net emissions.

h. Enable freedom for individuals and communities to choose between a system that pollutes and depletes the environment (the AC grid) and a newer pathway that prioritizes the individual and the planet.

i. Enable householders to form small cooperatives to solve their electricity needs locally, off-grid, and away from the public grid.

j. Promotes environmental education for consumers towards becoming carbon neutral on their free will, beyond traditional educational channels, national boundaries or political agenda.

k. Enable motivational mechanisms to rationalize consumption without losing comfort, leading to a reduction in carbon footprint.

l. Empowers individuals and communities to improve habits, reach net-zero emission on their own houses, and expand that mindset to street blocks and regions.

1.8. RESEARCH LAYOUT AND STRUCTURE

The structure of this dissertation is shown in Figure 04. Chapter 1 provides a broad overview of the research's rationale, motivation, objectives, aims, and significance. Chapter 2 includes a literature review on the domains covered in this research: GHG emissions, Small-scale power plants (*microgrids, nanogrids*, and *picogrids*), Blockchain, Internet of Things, Artificial Intelligence, and Sustainability. Chapter 3 provides an overview of the methodologies adopted for each research objective;

Chapter 4 presents exploratory research for the emission root causes; Chapter 5 presents two conceptual design models as solutions for emission problems, the ADCx and BAIoT models; It also presents 12 foundational principles for the BAIoTAG framework; Chapter 6 presents a proof of concept experiment demonstrating how Blockchain, AI, and IoT can contribute towards supporting small-scale and autonomous DC power plants. Chapter 6 also presents a comparative case study for

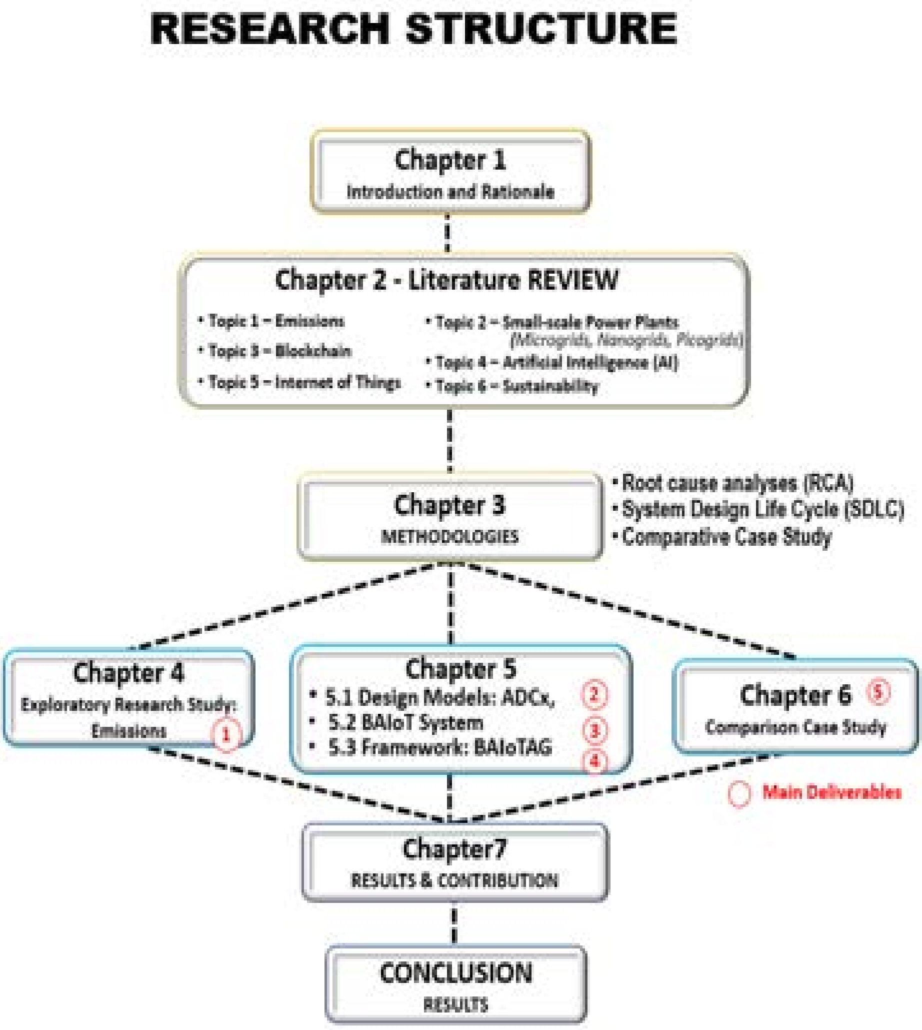


Figure 4: Thesis layout and structure

microgrids, *nanogrids* and *picogrids,* demonstrating how a ML model can support ADCx-BAIoT models. Chapter 7 presents the conclusion and future research work on the topic.

Chapter 2: Literature Review

As established in Chapter 1, there are six domains covered in this literature review: a) greenhouse gas emissions, b) small-scale DC power plants such as *picogrids*, *nanogrids* and *microgrids*, c) Blockchain, d) IoT, e) AI, and f) sustainability. These topics have been extensively explored in the literature; however, combining all these fields under a single framework is one of the unique contributions of this research. The following section presents a brief literature review on each of the topics.

2.1 GHG Emissions and GHG Effects

GHG effect refers to the natural process of thermal calibration of a planet, which took millions of years to reach the current state. This phenomenon is not exclusive to Earth. Part of sunlight reaches the thermosphere and is reflected back to the exosphere (outer space). The other amount reaches the Earth's crust, where the surface absorbs a portion, and the remainder is reflected towards the troposphere. Albedo is a unitless quantity, from 0 to 1, measuring how well a surface reflects solar radiation. Zero (0) refers to a perfect absorber, the black colour; One (1) meaning white, a perfect reflector. The thermal calibration produced by the GHG effects is critical to sustaining life on Earth. It plays a critical role in maintaining the Earth's overall temperature - without the GHG effect, rather than the 14°C average, Earth's temperature would drop to -19ºC, and life would not be sustainable [63].

The GHG effects were first noticed by Joseph Fourier in 1827, empirically validated by John Tyndall in 1861, and measured by Svante Arrhenius in 1896 [64]. The energy transformation processes from fossil feedstock into electricity generation, fuels for vehicles, household consumption, and industrial processes all contribute to the disturbance of GHG effects on Earth's atmosphere. Whereas carbon dioxide (CO_2) is the main gas exerting control over the strength of the terrestrial GHG effects [65], it is a key element for sustaining life on Earth - as every living creature relies on it for survival.

GHG emissions refer to any pollutants released into the atmosphere resulting from anthropogenic activities (produced by humans). GHG emissions are derivatives of labour activities. According to Adam Smith, "*the cause of the increase in national wealth is labour*" [66], implying that emissions, labour, and economics are strongly connected. Emissions are released in the same proportion that goods and services are produced. The causes of emissions are related to industrial processes, construction and agriculture activities, transportation – and more. People usually do not visualise, smell, or sense the emissions, so they have difficulty linking the objects and infrastructure around them with emissions. E.g., the higher the development of a country, the greater the infrastructure such as roads, buildings, hospitals, and schools – which denotes a greater amount of emissions being released to enable those constructions. If it is possible to measure the amount of goods consumed, exported, and imported into a country, then it is possible to estimate the level of emissions. However, global trading brings many complexities.

On a global average, the major GHG emissions found in the troposphere, ordered by mole fraction, are carbon dioxide (CO_2), nitrous oxide (N_20), methane (CH_4), Ozone and halogenated gases (containing chlorine, fluorine, or bromine) [67]. Water vapour is also a type of GHG gas, although not generally framed as an anthropogenic gas. However, water vapour stays in the atmosphere only for a short period (around a week) compared to the other gasses. Under a million-year time scale, volcanoes represent the main supply of atmospheric car dioxide, rock weathering is the main sink, and the biosphere behaves as both source and sink [68, 69]. On the other hand, the volcanic flux of CO_2 into the atmosphere remains two orders of magnitude lower than anthropogenic fluxes of CO_2 [70].

Since Industrial Revolution, CO_2, CH_4, N_20, and fluorinated gases (SF_6, HFC, PFC, NF_3) have been released into the atmosphere at disturbing rates. The increase in these gases changes the atmospheric concentration rates and organic properties, impacting Earth's natural equilibrium [71]. The anthropogenic GHG emissions from energy activities exceed all the other human activities combined [65].

The adverse effects of global GHG emissions have far-ranging environmental and health effects. It includes global warming, extreme weather and increase in the natural disasters trend, interference with the physiology of plants, destruction of biodiversity causing degradation and fragmentation of habitats, reduction of species, lowering reproduction rates and introduction of alien species, and more.

The standard measurement unit to quantify GHG emissions is *carbon dioxide-equivalent*, CO2e, a metric system adopted by the United Nations Framework Convention on Climate Change (UNFCCC). The referential unit (CO2e) becomes necessary since several other gasses have different properties, causing distinct effects over a period. The carbon dioxide equivalent (CO2e) represents the sum of GHG effects, including all gases (converted in their CO2e form), providing the total greenhouse gas emissions.

GHG emission problem has continuously been reported for over a century [72, 73]. In the 1960s, the evidence for the warming effect of CO_2 emission became increasingly convincing. In the 1970s, scientific consensus progressively backed the warming viewpoint. By the 1990s, when more accurate computer models became available, numerically confirmation was possible by the theory of the ice ages, the Milankovitch cycles theory. A dozen of teams around the world used computers to integrate results, observations, and theory [74]. Less than a decades ago, a broadly accepted consensus was reached that climate changes, anthropological (man-made) activities, and CO_2 emissions are all interrelated [75, 76].

The Intergovernmental Panel on Climate Change (IPCC) reports include all the research from the last first years explaining the causal relations of anthropological global warming [77]. The mitigation of GHG emissions is a debatable topic. The notion that UN members follow the IPCC recommendations in good faith to reach a net-zero balance (GHG emitted x removed) around 2050 [78] is excessively optimistic. Nations with a treemap exporting based on mining and fossil fuels (e.g., Russia, Australia) have very different per-capita electricity needs from those relying on the exporting software or telecom products (e.g., United Kingdom, China). Besides, the socio-economic-politic realities are specific to each country – and when sovereignty, cultural aspects, and lack of cross-country regulations are brought into the equation, the Paris agreement becomes a long wishing list to be contemplated by bureaucrats.

GHG footprint, or depending on the context, carbon footprint, refers to the sum of all greenhouse gas emissions related to a product, facility, person, service, or activity. It can also be calculated to a specific event, such as a trip, process, or method, during a period. When it involves a facility (e.g., house, commercial unit, factory), it must include all emissions embodied in (a) during construction, including material, manufacturing, services and transportation, (b) renovations, replacements or building maintenance, (c) consumer goods, appliances, and any manufactured product inside the house, (d) operational emissions for the household, such as electricity and fuels, and then (e) emissions related to disposal and waste. Every individual has a GHG footprint (or carbon footprint equivalent) that can be measured according to the total amount of GHG released into the atmosphere. For instance, residents of the USA (or Canada, Australia) have a much higher carbon footprint than other parts of the planet. The decomposition of the carbon footprint into the distinct consumption domains reveals that income distribution is directly linked with carbon footprint [79]. In especially affluent suburbs in the USA, emissions can be 15 times higher than in nearby neighbourhoods [80].

2.2 AUTONOMOUS DC POWER PLANTS

A web search in Google Scholar on the term "autonomous DC power plants" returned zero results at this writing. Another search, this time "autonomous DC microgrids", returned only four academic papers, however, none of them is related to the autonomy aspects proposed in this study, which captures the concept of being isolated from the AC power grid. The 'autonomous' keyword, depending on the context, can refer to systems that operate off-grid, islanded, standalone, or isolated modes.

2.2.1 Microgrids

The concept of power *microgrids* has existed for over a century since electricity became a public utility service. The 1880-1890 decade is widely known as the electrification decade. The Manhattan Pearl Station, built by Thomas Edison around 1882, initially serving 82 customers and covering a few street blocks was essentially a *microgrid* [81, 82]. Many small-scale power plant projects took place worldwide, in Germany, France, Belgium, USA, and Japan, and each was an independent *microgrid* [83, 84]. Over the next century, *microgrids* grew more extensive, integrated, segmented, regulated, and transformed into the existing AC power grid.

The *microgrid* concept has been explored more recently as part of the low-voltage distribution systems [85, 86, 87, 88] as a decentralised approach to supply electricity for a cluster of users –similar to a century ago. However, it may include multiple power generation sources, storage units, power electronics and communications links.

Microgrids are often framed as micro-cells within the larger AC microgrid, although this may not always be true.

The Consortium for Electric Reliability Technology Solutions (CERT) describes *microgrids* as "*Interconnected sources of distributed energy resources (such as solar and wind power), energy storage, and electrical loads that can operate either independently or connected to a surrounding electricity grid…"* [89, 85]. The International District Energy Association (IDEA) defines a *microgrid* as a "*local electrical systems that combine retail loads and distributed generation*, *may include integrated management of thermal and electrical loads, thermal and electrical storage, or a 'smart' interface with the grid, operating in parallel or in isolation from the grid."* [90]. Another interesting definition, places *microgrids* as a "*subset of the main power grid*", or some system that has been created for "*evolving the power grid*" [91]. The Department of Electricity (DOE, USA) defines *microgrid* as a *"group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode."* The European approach for *microgrids* can be typified in the EU Research Project, which defines a *microgrid* as a "*low voltage distribution network comprising various DG storage devices and controllable loads that can operate interconnected or isolated from the main distribution grid".* There are many biases, controversies and limitations around the definition of microgrids. In general, definitions of technology are dynamic and can vary in time, location, and context.

Under this study, a *microgrid* is a small-scale power plant supplying electricity to users, residential, commercial, or industrial users. The operation, the type of current (AC vs DC), the voltage levels, the connectivity aspects concerning the AC grid, the location, e.g., urban vs remote, those extra details are accessories to the term and therefore not part of the definition.

The current literature classifies microgrids under two major categories: (a) a group of power sources and loads normally operating in connection with and synchronous with the traditional wide area AC grid. It may automatically (or manually) connect or disconnect from the grid depending on the circumstances, such as security, features, capacity, economic viability, emergency, and operational constraints. When connected, it may supply power to cover shortages and increase the resilience of the main grid. (b) the other use application is for remote locations where power transmission (or distribution) becomes challenging or financially inviable. There are also institutional *microgrids* (e.g., university campuses, commercial or industrial facilities), special communities, and military bases *microgrids*.

A hierarchical organisational scheme for AC Microgrids with a clear distinction between *microgrid*, *nanogrid* and *picogrid* concepts and design alternatives such as operation modes, communication protocols and business models have been proposed by [88]. The authors organised the work by classifying *microgrids* into four functional levels, inspired by the Smart Grids architectural approach. Layer 1 describes the different physical devices involved in Microgrids, such as generators, converters, electrical vehicles (EV), energy storage systems (DS) and the DC levels involved. Layer 2 focuses on the communication protocols currently used or proposed. Layer 3 covers the intelligence aspects and decision-making issues related to the operations and strategic planning to maximize its potential. In the fourth and last layers, the authors review different business models, enlisting practical Microgrid experiences worldwide and classifying them according to the issues presented.

Figure 5: Number of publications last eight years on

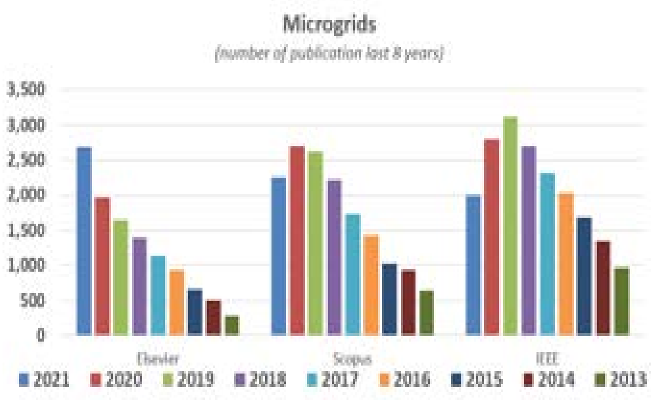
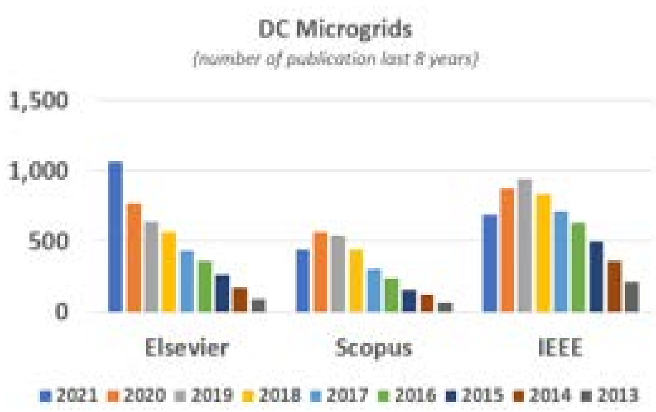


Figure 6: Publications last eight years on DC Microgrids



A greater portion of the literature on *DC microgrids* refers to standardisation, synchronisation, and controlling mechanisms when connected to the AC grid. Distributed cooperative control for DC *microgrids* has been asserted by many authors. For instance, Lexuan Meng et al. presented a broad analysis of control schemes, design, architectures, multilayer and

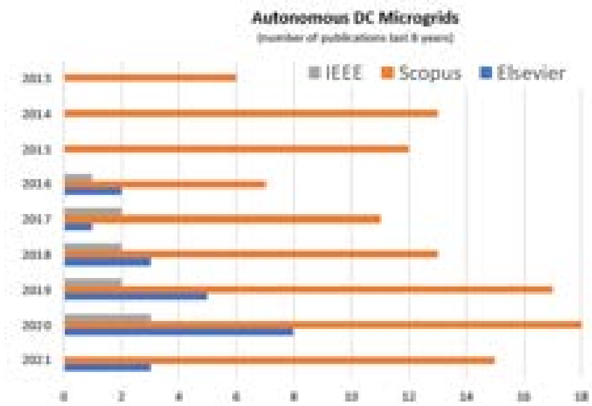


Figure 7: Publications last eight years on Autonomous DC Microgrids

coordinated methods, plug-and-play processes, stability, and clustering control [92]. Otsuji et al.. propose the concept of Resilient Electric Infrastructure Technologies, R-EICT, to improve resiliency through 5G/B5G mobile edge computing on overall optimisation of autonomous decentralised cooperative control of DC *microgrids* [93].

The number of academic publications in Microgrids, DC Microgrids, and Autonomous DC Microgrids over the last eight years have been depicted in Figures 5-7.

The concept of *autonomous DC microgrids* is fairly recent. [94] presented planning and optimisation of standalone DC microgrids for rural and urban applications in India. It included loads from a rural village, an urban residential building, and a business organisation. The Distributed Energy Resource (DER) consisted of photovoltaic (PV) solar, wind turbine, and biodiesel generators, all renewable sources. The authors used Homer Energy software to determine the optimal system configuration with the lowest energy cost. The study compared several cost components, electrical production, emission, and energy management. The study concluded that autonomous microgrids could provide a reliable power supply at a reasonable cost (U$0.27 per kWh).

Decentralised voltage control for autonomous DC microgrids was proposed by [95], which deployed a robust H∞ control system for the voltage control challenge. The system consisted of multiple distributed generations systems - where the one degree-of-freedom (DoF) structure of the developed control system ensures the robust system performance and stability to counterbalance the stochastic nature of multiple energy sources. The efficiency of the suggested controller was analysed by simulating several scenarios using MATLAB and SimPowerSystems Toolbox. The system performance was validated through experimental studies.

A decentralised dynamic power-sharing strategy for hybrid energy storage systems was suggested by [96] for an autonomous DC *microgrid*. It used an extended droop control

(EDC) strategy to reach dynamic current sharing autonomously during abrupt load change and power source variations. The procedure consisted of a virtual capacitance droop controller and a virtual resistance droop controller for power storage. The implementation also included battery and supercapacitor (SC) as supplementary features. Allocated power can be challenging in autonomous microgrids since power generation and storage costs vary with the distribution and intensity of the loads.

Several engineering modelling and simulation tools have been developed for microgrids. The tool may contain biases around the definition of microgrids. Some tools only work within the AC grid realm, which may preclude using DC autonomous grids. These tools primarily focus on economics, operations, electric effects, control mechanisms, and stability. Some prominent tools are the DER-CAM, Homer-Energy, OpenDSS, CYMDIST, GridLAB-D and PowerWorld.

DER-CAM (Distributed Energy Resources Customer Adoption Model) was built by Lawrence Berkeley National Laboratory [97]. It can include passive measure enhancement options in the optimisation process and the standard Distributed Energy Resources (DER) investment options such as local renewables or micro combined heat and power (CHP). DER-CAM is capable of deciding on implementation costs and performance. It allows passive improvements such as exchange of windows, and doors, increased insulation, and width on the wall, ground, and roof. These extra capabilities provided by the tool were not previously covered by the DER-CAM tool, and have now been explicitly addressed in the more recent DER literature [97].

Homer Energy was conceived and built by the National Renewable Energy Laboratory (NREL) and is now commercialised by Homer Energy LLC, is a microgrid power optimisation model helping to design off-grid and grid-connected systems. Given a range of power loads and distances, Homer runs cost sensitivity analyses and finds which combination of resources can meet the electrical and thermal demand [98, 99].

OpenDSS was developed by the Electric Power Research Institute (EPRI) – it is a tool for power distribution system simulation, also known as DSS, focused on distributed resource integration and grid enhancement endeavour [100].

GridLAB-D was built by the U.S. Department of Energy (DOE) at Pacific Northwest National Laboratory (PNNL). GridLAB-D is also a DSS tool, for power distribution analysis tools supporting the design and operation of power distribution systems. It incorporates advanced techniques and high-performance algorithms to deliver the best in end-use modelling and can be combined with a range of integrated software tools for several power distribution systems, and analysis tools [101].

CYME International developed by CYMDIST can support planning analyses, simulation of operations, power safety, assessment studies and distributed energy resources interconnection. It can model various scenarios in a distribution system and focus on dimensioning, system capacity, emergency, power quality and network optimisation [102]. CIME offers a wide range of options for batch analyses – and allows PYTHON scripting, Component Object Modelling (COM) capabilities, and time-series simulations.

PowerWorld Simulator from PowerWorld Corporation provides simulation and visualisation software to the global electric power industry, such as transmission planners, power marketers, power utility service providers, and instructors [103]. Based on [104], OpenDSS and GridLAB-D displayed a "high capability to simulate networks with fluctuating data values, using data that changed on a minute interval". The process is effortless, allowing interactive simulation through a batch mode simulation function. This happens through a sophisticated process known as "Time Step Simulation".

2.2.2 Nanogrids

The *nanogrid* concept has been found in the literature for decades. Usual focuses are on power management, ability to work islanded vs grid-connected modes, system control, energy trade, and applications in remote locations [105, 106, 107, 108]. Some authors refer to it as a house, a group of houses, remote communities, a rural area or even an island. In most recent years, the concept of DC *nanogrids* has also been proposed; however, in most cases, they are connected to the AC grid or some hybrid DC/AC system, therefore not matching the concept of a purely autonomous DC small-scale power plant as proposed on this research. [109] performed multiple studies on a hybrid DC/AC *nanogrid* configuration for a commercial building. The goal was to compare the original AC system's electrical performance and energy efficiency to the finalised DC system and present a reproducible topology for future research projects. [110] presented a mode control strategy for a converter-assisted self-excited induction generator (SEIG) based on wind power in a DC *nanogrid* application. Except for a few special use cases, autonomous DC *nanogrids* have been proposed, but only for remote and isolated areas [111, 112, 113, 114].

An autonomous, decentralised, flexible, control strategy for DC nanogrids in remote areas (islands) has been proposed by [115]. It does not require a communication system, and the management strategy is in hierarchical control. The primary control can leverage the current for the internal bus voltage. In contrast, the secondary control can restore the DC bus voltage deviation caused by droop operation. The exchange of power can be controlled through algorithms, which provides greater flexibility for the nanogrids, towards ensuring autonomy. It also supervises the variation of the battery power and the DC bus voltage for the interconnection without any extra communication link.

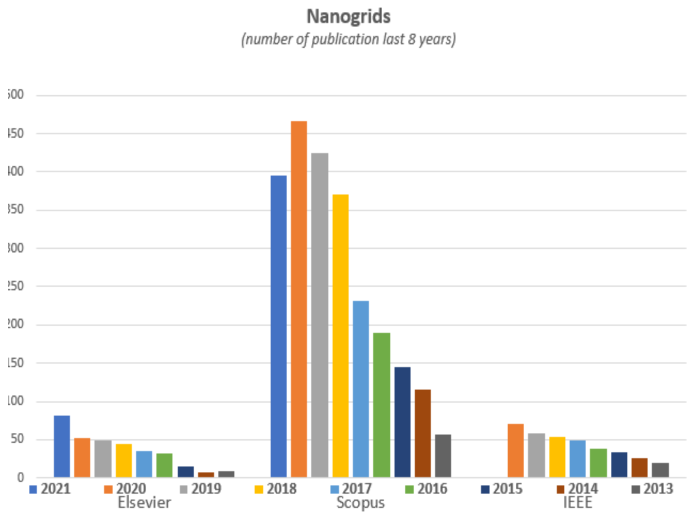


Figure 8: Publications last eight years on 'nanogrids'

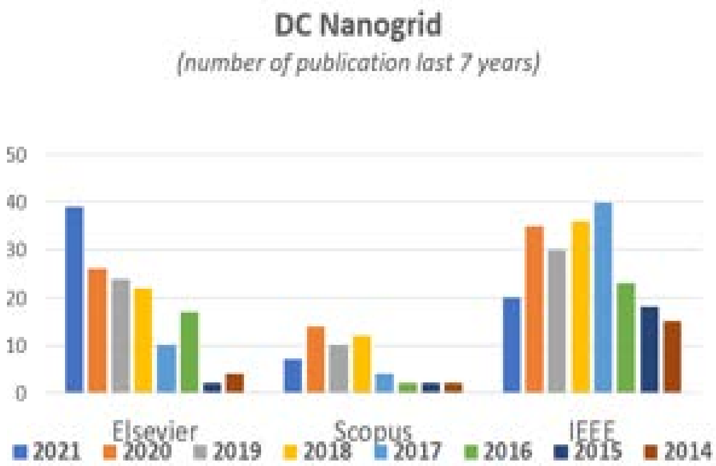


Figure 9: Publications on 'DC Nanogrids in the last eight years

The number of publications on *nanogrids, DC Nanogrids* over the past 8 years are shown if Figures 8-9.This research identified only one publication that could be classified under the *autonomous DC Nanogrids*.

2.2.3 Picogrids

The term *picogrid* has been found in the literature, however unrelated to small-scale power plants, which concerns this research. [116] proposed a *picogrid* controller using Hidden Markov Model to manage power storage for uninterrupted DC appliances. [117] [117]

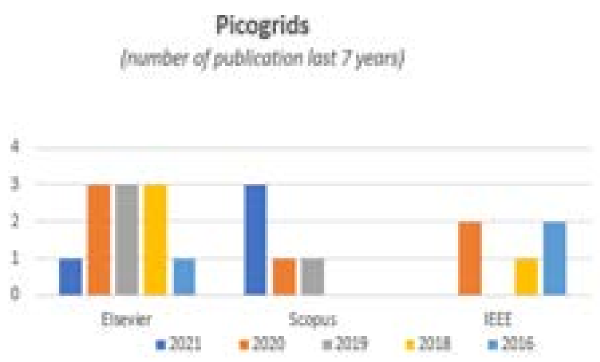


Figure 10: Publications last seven years on DC Picogrids

proposed a personal comfort system for power backup of a *picogrid* consisting only of a LED light and a DC desk fan. [118] proposed a method of automatically measuring power usage, identifying and classifying devices using neural networks, and named the measurement system a *picogrid*. Figure 10 show the number of publication in Picogrids between 2016 to 2021.

2.2.3.1 Femtogrids

The concept of femtogrid has been introduced in this study, a new terminology to support users in raising awareness according to the use category. Each femtogrid represents a group of electrical circuits in a use category and can help in a *picogrid*, *nanogrid*, and *microgrid* environment.

Load categorisation is an important aspect of facilitating the monitoring, supervision, and data acquisition of appliances and devices. A fine-graining classification enables a better understanding of the overall characteristics of a house or a cluster of users within a region. It helps determine what parameters can most influence a group of users or what policies could be introduced to correct a distortion in consumption, which ultimately reflects in GHG emissions. For instance, the building characteristics, shape, size, and materials affect user behaviour. Householders might have prioritised aesthetics over energy efficiency, which later would highly impact the consumption trend. The form, size, orientation, external and internal material, and fabric choices highly influence heating and cooling. The number of windows and doors, lighting, fans, and type of space cooling can also affect energy consumption. Many appliances are less influenced by their surroundings and more by the users (e.g., cooking, TV, fridge) [119].

A patent for femtogrid has been founded for an "*electrically parallel connection of photovoltaic modules in a string to provide a DC voltage to a DC voltage bus*" [120], which does not share any overlap with this research. The term has been used in the mobile phone industry representing a small coverage area and in energy harvesting applications. All these cases do not share an association with the concept of Femtogrid proposed in this study.

Under the ADCx model, nine femtogrids, or nine use categories, have been proposed: (a) lighting, (b) food preservation, (c) cooking and water heating, (d) labour-saving and mechanical tools, (e) education, communication, gaming (f) space cooling and heating, (g) hygiene, (h) outdoor entertainment and (j) electric vehicles. Since these use categories have specific consumption profiles, the use disaggregation becomes paramount to combat power waste and improve consumption habits.

2.3 BLOCKCHAIN

Around 1978, "block chaining" was introduced as a cryptographic process addressing data security, message verification and error detection in data communication between a computer processor and a remote terminal [121, 122]. Thirty years later, in 2008, the expression 'chain of blocks' surfaced in the context of electronic cash, allowing online payment without the intermediation of a traditional financial institution Bitcoin used a comprehensive technological apparatus, including public-key cryptography, game theory, peer-to-peer computing, digital signature, and consensus protocol, to solve the double-spending and fault tolerance problems without relying on a third party for management. As put by [123], Bitcoin relied upon a "*proof of work scheme for timestamps transactions and hashing them into an ongoing chain of hash-based proof-of-work, forming a record that cannot be changed without redoing the entire proof-of-work. The longest chain served as proof of the sequence of events, which could be verified by other nodes and confirmed by the largest CPU power pool. As long as most CPU power is controlled by nodes not cooperating to attack the network, the longest chain and outpace attackers.*"

In 2011-2013, 'block chain' was mentioned in several reports to describe a public and distributed ledger [124, 125, 126], and in 2014, 'Blockchain' emerged as a single word [127, 128]. Around that time, several scandals occurred, including hacking and illegal activities involving Bitcoin [129, 130, 131]. The shift from Bitcoin to Blockchain happened gradually, though the path of least resistance [132] and some entrepreneurs realised the technical potential and business prospects beyond cryptocurrency. Bitcoin's codebase limitations became an obstacle to developers. Restrictions in the programming language, block sizing, storage capacity per transaction, and several developers realised newer approaches were required.

Around 2015, the narrative changed, and Bitcoin became just a relative to Blockchain, sometimes referred to as 'the technology behind Bitcoin'. Blockchain is still evolving and adapting according to the context and application. Several white papers and books were published on Blockchain [128, 133, 134, 135, 136, 137]. Given its key characteristics for sharing information between peers and chronologically ordering messages and transactions, it became Blockchain technology.

Ethereum was launched in 2015 as an improvement of Bitcoin. It introduced new features and expanded the portfolio of use applications; however, it failed to address the scalability problem faced by Bitcoin. As of Mar 2022, proof of work remains the consensus protocol used by Ethereum, despite many vows to switch to proof of stake (PoS). It is a decentralised platform for distributed applications (DApps) development based on a Turing complete language which allows a broader range of computation. Consequently, it permitted more sophisticated programming code logic and rich statefulness, providing transparency at the Blockchain level. That enabled the deployment of smart contracts and opened possibilities in many use cases. Smart contracts are codes embedded in Blockchain software applications to automate tasks between network participants. The key benefits are cost reduction, decreasing time processing and speeding up business. The tasks can be any contractual obligation triggered by internal or external events that can be coded and linked to the Blockchain network. *Smart contracts* are self-executable, automated, self-enforceable, and capable of generating invoices, payments, billing, receipts, sending messages, and many other tasks.

Ethereum was the first Blockchain-oriented platform specially designed to support *smart contracts*. Compared to Bitcoin, the key technical advances of Ethereum include the reduction of block validation time, greater block capacity, higher throughput (transactions per second) and the use of the Elliptical Curve cryptographic algorithm rather than RSA.

Hyperledger and R3 consortiums were formed by the end of 2015. Both organisations focused on *smart contracts* and DApps in a permissioned environment for business purposes. The terms 'Blockchain' and "Distributed Ledger Technology" (or simply DLT) have been widely used in marketing material [138] [139]. DLT and Blockchain have some overlapping in meaning, and depending on the context, they may refer to the same concept. In general, DLT is used as a private network and Blockchain in a public network.

Hyperledger consortium has over 200 affiliated organisations including ICT, financial services and academic institutions is an umbrella open source project hosted by the Linux Foundation founded in 2015. It focuses on the collaborative development of distributed ledger technologies. Hyperledger has several working groups and frameworks such as Hyperledger Fabric, Iroha, Sawtooth, Burrow and Indy. Hyperledger Fabric enables plug-and-play modules, such as membership services, and consensus policies. It offers distinctive approaches to consensus, which allows methodologies for prioritising tasks, and performance at scale, while safeguarding privacy, and anonymity. It enables a broad range of applications, such as supply chain, digital identity, on-demand service deployment, and ordering services [138].

The distributed ledger platform of R3 is called Corda and specifically focuses on *smart contract*s and DApps solutions [140]. Corda is an open source and geared towards the financial system and commerce. Both Corda and Hyperledger platforms have been inspired by Blockchain technology, but they have significant technical differences and purposes. R3 is a consortium started in 2015 with over 200 members in the research and development of distributed ledger technology.

Although DLT and Blockchain platforms are geared towards *smart contracts*, they have distinct architectural approaches. While the key propositions of Blockchain rely on censorship resistance and transparency, the DLT's main value propositions are the high throughput and the need for registration with a central authority. Blockchain allows anyone with a computer or mobile technology to download an application and participate in the peer-to-peer network with a certain degree of anonymity, however free from central management or censorship. In contrast, DLT is a private network, requiring all users to be registered and authorised before accessing the network.

The trade-off between censorship freedom and throughput is patent as Blockchain requires a mechanism for ordering and validating transactions. A cryptographic mechanism achieves this through the chaining of blocks, hence "Blockchain". All transactions in Blockchain undergo a consensus protocol involving thousands of distributed nodes. These

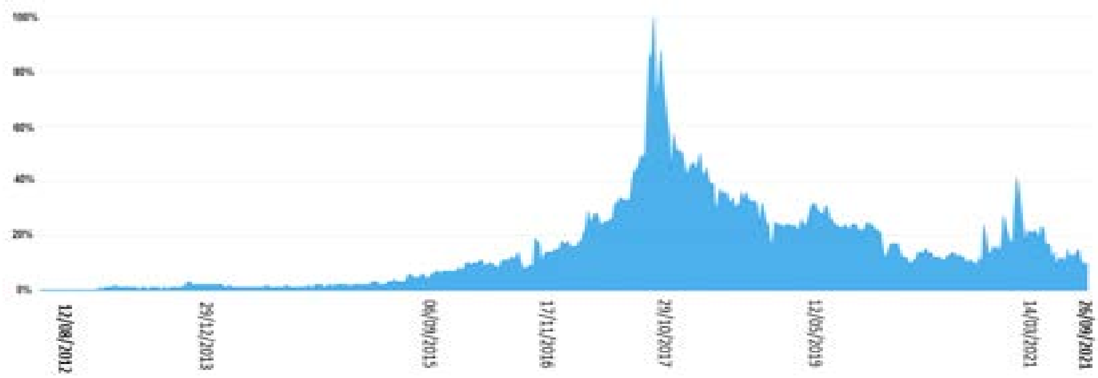


Figure 11: Blockchain Search Volume (Google Trends)

transactions are processed, ordered, validated, and account for fault tolerance and security issues. As nodes are geographically distributed, untrusted, and with different resourcing capabilities, it takes much longer to process and validate the transactions in Blockchain networks compared to DLT. Since DLT relies on a centralised architecture to provide transaction validation and ordering functionalities, it does not need to undergo the 'chaining blocks' mechanism. Therefore, DLT is capable of delivering much higher transaction volumes. Figure 11 shows the number of searches in Blockchain ("Google Trends"), while Figure 12 depicts the number of academic publications in Blockchain between 2014 to 2021.

Blockchain or DLT can offer advantages depending on the use case. Blockchain offers transparency and freedom from censorship; however, it has low throughput, and scalability can be challenging. DLT provides higher performance and scalability but requires a central trust authority to register and validate the transactions. EOS is a newer open source

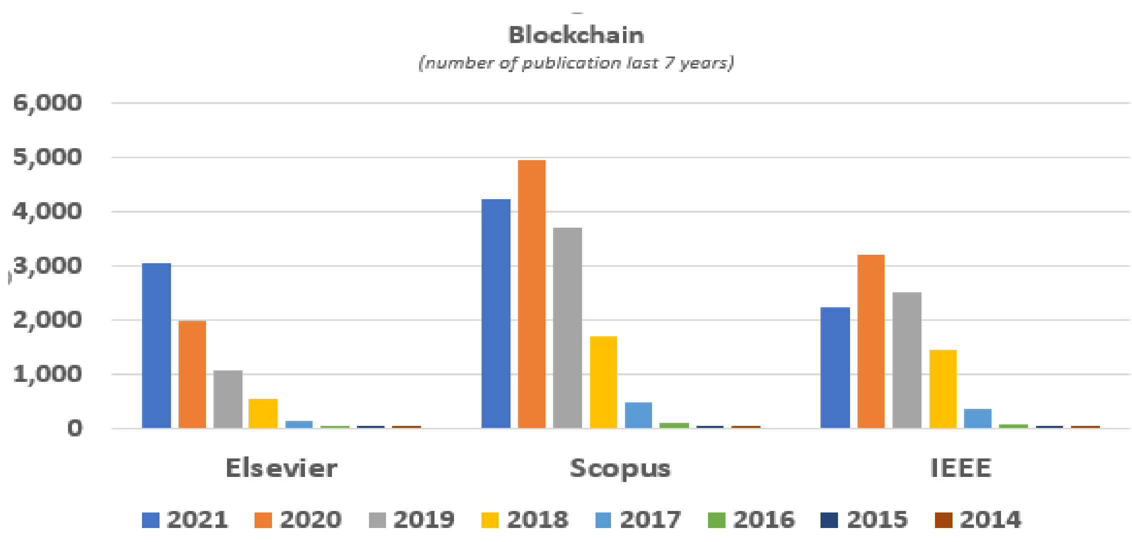


Figure 12: Number of Publications over last eight years in 'Blockchain'

Blockchain platform that was released in 2018 aiming to deliver decentralised applications, and hosting *smart contract* capabilities. EOS also offers decentralised storage for enterprise solutions, in an attempt of avoiding potential scalability issues such as those faced by Bitcoin and Ethereum. EOS recently claimed 5,000 transactions per second, with no fees [141, 142]. NEO is also a Blockchain platform that claims over 1,000 transactions per second. For the moment (Q3_2018), it is a decentralised architecture but not distributed due to its Distributed Byzantine Fault Tolerance (dBFT) governance system.

2.3.1 Blockchain Building Blocks

Blockchain remains an unconventional concept with various interpretations since its building blocks can be configured and tailored according to the application. It may prioritize different aspects, serving distinct purposes, covering many useful applications, and targeting specific features. The term Blockchain can refer to a:

- a type of decentralised peer-to-peer computer network.
- a type of database for recording digital transactions, or a distributed ledger technology (DLT),
- a peer-to-peer digitalised money transfer mechanism.
- software platform for decentralised applications.
- any data construct based on a consensus protocol combining cryptography and a ledger;
- a decentralised ledger featuring consensus protocol, cryptography and a public or private ledger;
- a private network that uses cryptography and consensus protocol for governance purposes

•	a business ecosystem around crowdfunding and capital fundraising for start-ups.

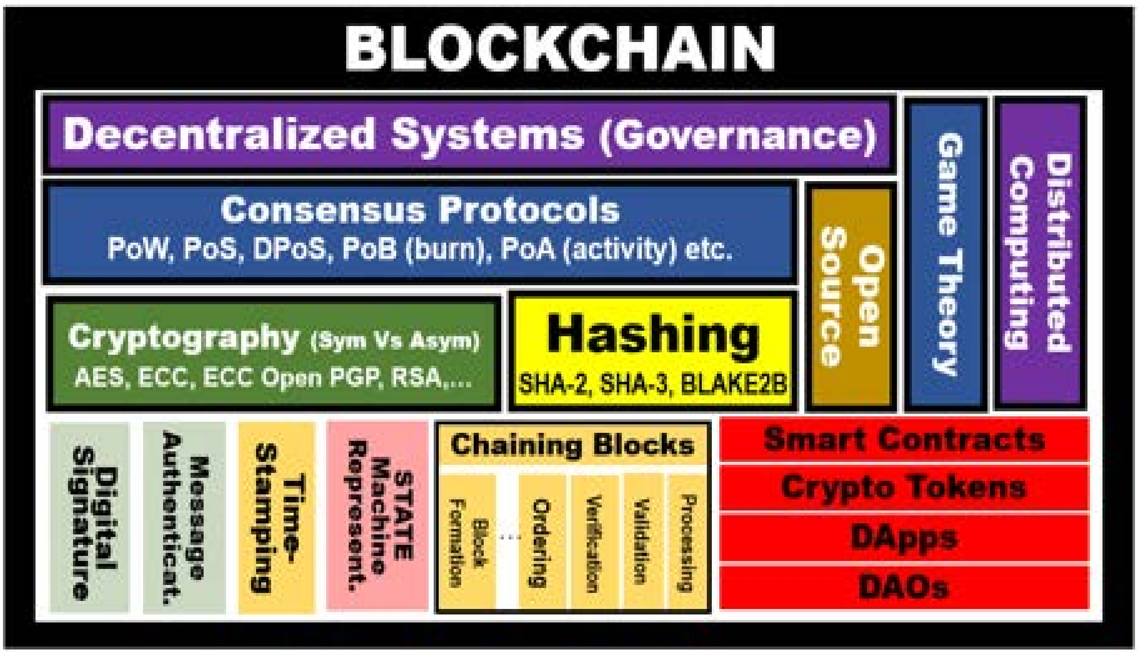
Figure 13 illustrates the main building blocks of Blockchain technology: (A) Decentralisation, (B) Consensus Protocol, (C) Cryptography, (D) Distributed computing, (E) Digital Ledger, and (F) Software. Each domain is covered below:

Each Blockchain has its specific attributes, value propositions, benefits and limitations. Newer developments overcome past challenges, introduce new concepts, and open new possibilities. The main components and functionalities of Blockchain are discussed: (a) cryptography, (b) decentralisation, (c) peer-to-peer networking, (d) tokenisation, (e) *smart contracts*, (f) digital ledger and (g) open software platforms. These attributes are now explored:

A- CRYPTOGRAPHY

The concept of 'block chaining' has roots in cryptography, applied mathematics, computer science, probability theory, algorithm number theory and information theory [143, 144]. The cryptography concept has been around for thousands of years and is found in all major civilisations [145]. Julius Caesar was known to use a form of encryption to communicate to his army generals through secret messages during wartime [146]. When electricity became popular in the 20th century, Herbern developed an electro-mechanical contraption, the rotor machine [147].

Figure 13: Blockchain – Technological Stack and Ecosystem



The Enigma machine emerged at the end of the First World War and was intensively used during the Second World War [148]. The articles "A mathematical theory of cryptography" [144] and "*A Mathematical Theory of Communications"* [143] both became a landmark in cryptography; Thirty years later, around 1976, Whitfield Diffie and Martin Hellman introduced the key distribution, known as "*Diffie–Hellman key exchange*" [149]. In 1978, Leonard Adleman, Ron Rivest, and Adi Shamir, motivated by the published works of Diffie-Hellman, implemented the RSA algorithm, best known public key algorithm for a long time [150]. Digital signature [151] [152], and message integrity verification [153], all contributed to the emergence of digital money. Next emerged the *one-way hash trapdoor function* [149], Merkle tree [154], proof of work for combatting junk mail [155], and several other data constructs [155], all of these achievements contributed to solving earlier Internet problems and then the Blockchain technology.

The Elliptic Curves Digital Signature Algorithm – ECDSA is the most used in Blockchain, instead of RSA. This is justified because the 256-bit elliptic curve private key is smaller, easier to manage and thought to be as secure as the RSA digital signature. The elliptic curve equation used for most cryptocurrencies is $y^2 = x^3 + 7$. It builds upon that a non-vertical line overlapping two non-tangent points will always cross the third point on the curve. ECDSA has robust properties but can be fragile if not handled with care [156, 157, 158]. Remote timing attacks have been an active research field in applied cryptography which could exploit cryptosystems or protocol implementations that do not run in constant time [159]. There have been political and technical concerns around ECDSA, and securing dangers of the NIST curves [160, 161].

Blockchain platforms such as Ethereum, Bitcoin, and EOS use cryptography to authenticate the sender, timestamping, ordering, verifying and validating the transactions, and ensure that records have not been tampered. Cryptography also provides integrity, non-repudiation and availability for network users - and, depending, some degree of confidentiality (privacy) through pseudonymous. The consensus algorithm includes the functionalities enabled by cryptography. A hash function cryptographically links a chunk of transactions into a block and subsequently chains the blocks, which justifies the portmanteau 'Blockchain'. Bitcoin uses RSA algorithm and SHA 256

On the other hand, DLT technologies such as Hyperledger and Corda tend to be centralised platforms and may use a certificate authority responsible for verifying ownership, transaction validation, and creating trust among users. Depending on its design, DLT technologies do not have to create blocks and link them to form a chain to solve the timestamping, double spending, and fault tolerance problems. Consequently, it is faster and has a higher throughput, although it is not censorship-resistant.

B- HASHING FUNCTION

A hashing algorithm takes an input of data, such as a string of text or number, any digital picture, sound, or video of any size or length, and creates an output of a fixed length. The input is referred to as 'message' and the output as a digest, hash values, hash codes, *message fingerprint,* or simply *hashes*. The values are indexed using a fixed-size table, known as the *hash table*. Given an input, it always returns the same result and speedily. Any construct capable of mapping input data of arbitrary size to fixed-size values is a hash function. Hash functions are determinist, also referred to as a one-way functions. It is infeasible to reverse a hashing output back to the original input, making it pre-image resistant. A small input change thoroughly changes the output, making it collision-resistant. A hash function H is collision-resistant if it is difficult, and impracticable, to find two inputs that lead to the same output; e.g., two inputs x and y, where $x \neq y$ but $H(x) = H(y)$ [162].

Hash code function has been extensively used in digital communications for many decades and it is a key component for digital signature, message authentication, content verification (integrity) and even encryption [163]. A cryptographic hash function is a particular class of hash functions with specific characteristics and attributes, making it ideal for cryptography. In a Blockchain context, the cryptographic hash function provides digital signatures for the transactions by authenticating the untrusted user.

The hashing function is a key mechanism within the consensus mechanism for creating and verifying new blocks (tokens). When proof of work protocol is used, the hashing function is the core mechanism by which the proof of the working functionality is carried. It controls the time by adjusting the degree of difficulty of the hashing computation.

The design of the hash function differs for each Blockchain network. Although they all share the same principle, the purpose and process may change according to the technical and business strategy requirements. Hashing algorithm designs influence transaction speed and have an associated computational cost, and the degree of difficulty impacts throughput. On cryptocurrency, it may favour using a certain category of mining hardware to the detriment of others, e.g., CPU Vs GPU, FPGA Vs ASIC. Below are some of the popular hash algorithms used in Blockchain:

- **SHA-256** (Secure hash Algorithm - 256 bit) is the most popular hash algorithm and is intensively used on many applications, including cryptocurrency. It generates a unique 256-bit (32-byte) signature for each transaction or the entire block. Block handling time for SHA-256 generally ranges from six to ten minutes and requires hashing rates in the order of Tera (10^12), Peta (10^15) or even Exa (10^18) hashes per second (EH/s) when performed by ASIC hardware. Some cryptocurrencies that use SHA256 are Bitcoin, NameCoin, PeerCoin, BitcoinCash. Typical hash rates for Bitcoin is around 150M to 240M [Terahashes/second] [164].

- **Scrypt Algorithm** requires large amounts of memory and has been specially conceived to execute large-scale custom hardware attacks. It is less computation-intensive and thus faster than the SHA-256 algorithm. GH/s measure Scrypt's hash rate up to TH/S depending on the Blockchain network for that particular cryptocurrency. Some cryptocurrencies deploying Script are Litecoin, Novacoin, and Latium.

- **X11 Algorithm** was created by the Dash core development team. It uses a sequence of eleven scientific hashing algorithms for the proof of work. It is more energy-efficient when compared to Scrypt or SHA256. X11 can be mined by CPU or GPU, and X11 hash rates are measured in Pico hashes per second (PH/s). Some implementations using X11 are Dash, StartCoin, and XCurrency.

- **Cryptonight Algorithm** was developed to meet CPUs and GPUs capabilities and employed in an open-sourced protocol that improves transactions privacy, "CryptoNote" privacy. Contrasting with the Scrypt algorithm, Cryptonight relies on previous blocks to assemble a new block, and its hash rate is measured in MH/s up to GH/s. Some cryptocurrencies deploying Cryptonight are Monero, Bytecoin and DigitalNote.

- **Dagger-Hashimoto-Ethash** was designed specifically to avoid mining with ASIC hardware. It is more processing-intensive, requires more memory, and consequently becomes more expensive to mine in ASICs hardware. GH/s measure Ethash hash rate. Some cryptocurrencies deploying Ethash are Ethereum, Expanse, Ethereum Classic and Metaverse.

C- PARALLEL, DISTRIBUTED AND PEER-TO-PEER COMPUTING

There are several methods, topologies and architectures for interconnecting computers: grid computing, cloud computing, utility computing, cluster computing, parallel computing, distributed computing and more. The selection for the topology or process may depend on the purpose and the specification of the computers, the aims and objectives of the network, type of problem(s) to be solved, costs, reliability, accessibility, availability, security, throughput, resilience, and the specific requirements from stakeholders.

Distributed computing is a branch of computer science focusing on distributed systems, which have components on different machines interconnected via a computer network. By passing messages among the nodes, it enables system communication and coordination actions. Several components mutually interact to achieve a common goal, acting as a single entity. The three most significant characteristics of distributed systems are the absence of a global clock, the concurrency of components, and the independence of the failure of components [165]. In the event of a component failure, it does not imply that the entire system fails. Fault tolerance is a key aspect of distributed systems. Figure 14 shows the five main criteria that combined, defines a distributed data processing system.

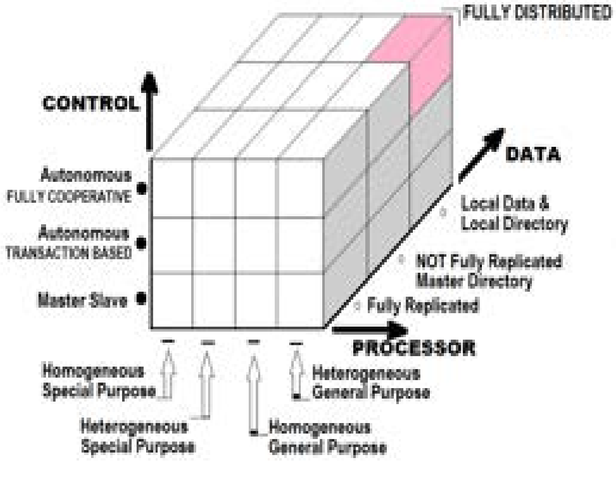


Figure 14- Distributed System Types (Enslow 1978)

Distributed systems can vary from service-oriented architecture-based to multiplayer online games to peer-to-peer applications, allowing machines to access a massive amount of data. It eliminates the single point of failure and reduces bottleneck problems. It eliminates the need for a centralised server through its self-maintenance capabilities. It uses idle resources across a large number of participants geographically distributed. It aggregates power to solve computational problems faster at a lower cost. In basic terms, a distributed system is a collection of autonomous computers interconnected via a distributed operating system. Independent computers are capable of coordinating activities and sharing the system's resources, and the user perceives the environment, as a unique, integrated computing system [166]. The same distributed operating system runs on multiple and independent machines – consequently, the users are unaware of the multiplicity of machines. Figure 15 shows the concept of distributed communications networks, proposed by Paul Baran, in the early days of the Internet.

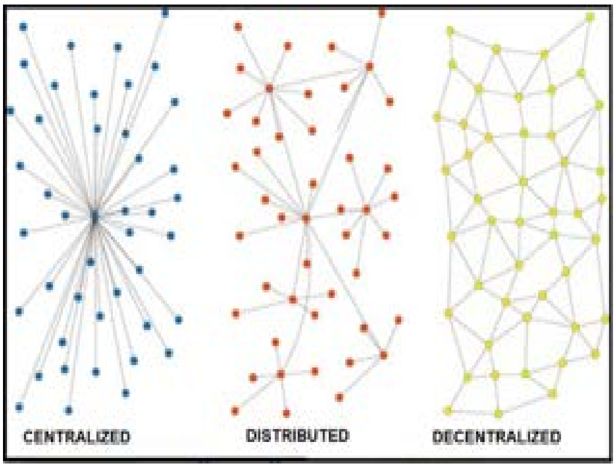


Figure 15 - Network Topologies (Baran, 1979)

The concept of distributed computing emerged in the 1970s [167] and became a branch of computer science around the 1980s as an alternative to centralised computing. The ARPAnet project, the Internet predecessor, was designed to model real-world peer-to-peer (1:1) direct exchanges. Other projects followed, e.g. Xerox PARC and Massive Parallel Machines-MPP. Distribution may refer to the hardware (processors), software (applications), communication control, computation, users or data. Distributed computing embraces many activities in the computer and communications space. It may refer to the Internet, wireless communication, cloud server, parallel computing, multi-core systems, and mobile networks. It can still refer to an ant colony, a brain, or the human society - as all could be classified as distributed systems [168].

Parallel computing systems are a predecessor of distributed computing. Whereas parallel computing breaks applications into tasks, which are executed *simultaneously*, distributed computing allocates an application into smaller tasks executed at multiple locations and different hardware [169]. Parallel computing, in most cases, denotes multiple processing elements existing within one machine. For that end, each processor is dedicated to the overall system at the same time. On the other hand, distributed computing involves a group of machines, geographically separated, each contributing to the processing cycles of the overall system, over a network, over time [170]. In parallel computing, all machines synchronise to a master clock (homogenous), whereas in a distributed system, there is no centralised clock (heterogeneous timing).

Distributed systems are a computing paradigm where a collection of machines (nodes) work simultaneously to achieve a common goal. As different components work in a coordinated fashion, end-users perceive it as a single logical platform [171]. A distributed system is characterised by the absence of a global clock, no centralised memory sharing, geographically separation, autonomy and software components executed in a concurrent process. The system's integrity relies on concurrent updates, which can jeopardise the entire system.

A node is any network participant of the distributed system capable of transmitting and receiving messages from other peers. Nodes can be trustable (honest), faulty, and exhibit arbitrary behaviour and the client algorithm should be able to detect it and take corrective actions. A node that can be intentionally malicious is also known as a Byzantine node. There may be different categories of nodes for different functions within a distributed system, such as validation and storage. The key question in distributed system design is the decision coordination process among nodes and the fault tolerance mechanisms. Nodes communicate via the message passing algorithm on each machine across the distributed network [39]. Distributed systems can be challenging to plan and run. The CAP theorem has been proved and states that a distributed system cannot the latest copy of the data, be 100% available at all times, and still ensure fault tolerance simultaneously [172].

Peer-to-peer (P2P) is an overlay application subclass within the distributed computing domain. It refers to the communication model, the interconnectivity between machines, where each party has the exact capabilities. Either party can initiate or interrupt a communication session without compromising the overall system. P2P explores applications on layer 7 of the OSI model, on edge with the end client. It sits on top of the Internet and therefore is referred to as an overlay network. However, it is not a conventional type of network, as all the nodes share storage, processing and networking bandwidth without central management. The critical difference between distributed and peer-to-peer computing is that the latter has no distinction between the nodes. All the nodes on a peer-to-peer network run the same software application, the same consensus protocol rules, and are referred to as equal peers.

A P2P architecture is a form of public cloud network where participants share information (database) and manage their network (cloud). It can be public or private, structured or unstructured, depending on how the software is designed. P2P manages and delivers its own content without a central party. It uses existing network infrastructure, low cost, low scale, and is shared virtually among a community of users.

The deployment of P2P networks has limitations. The absence of a trusted central authority to authenticate the user, and validate the transactions, has somehow to be compensated. The introduction of consensus mechanisms with rules and conditions fills the gap – at a cost. Depending on the consensus, there can be delays and costs associated. While it eliminates the single point failure for the entire network, each node becomes a network security target individually. For instance, if someone loses a password or a token on a traditional centralised network, the problem can be easily fixed by obtaining a new one. Contrariwise, password loss can imply a loss of assets for good on a decentralised network.

Blockchain is built on the concepts of distributed computing and P2P communication. The digital ledger used for Blockchain applications is a distributed program that runs within a distributed computing system, using the P2P communication model. Blockchain may be referred to as a distributed ledger technology or a peer-to-peer system depending on the context. However, the ledger itself is only one of many components of Blockchain technology. The ledger is always part of a distributed system, including many machines across a large geographical area. Distributed computing, as opposed to non-distributed models (e.g., mainframes), can have a varying degree of centralisation, spanning from full centralisation to full decentralisation. The ledger access rights and control depend on the centralisation level of the system's governance, which is further discussed in the next topic.

In summary, distributed systems refer to the geographical distribution of storage or processing capabilities, whereas communication and fault tolerance become key technical challenges.

D- DECENTRALISATION & TRUSTLESS COMPUTER NETWORKS

Centralisation versus decentralisation refers to the management of computing resources, access control, user rights, privacy and security. It is directly linked to organisational governance. Logics, maths, and computational theory were the foundational pillars of the computing age in the 1950s, and only large organisations dominated the computing market until the 1980s. Mainframe computers occupied large spaces, entire facilities, and dedicated users. In the early stages, two uses could not access the mainframe system simultaneously.

The terms ‘centralisation’ and ‘decentralisation’ are not restricted to the technical domain. Both concepts are regularly used in management, decision-making, political, business and industrial space. For centuries, the insurance segment has used the decentralisation concept to spread the risks across stakeholders for ships attacked by pirates. The democracy system, the printing press, and, more recently, the Internet are samples of the decentralisation concept.

All decentralised systems are distributed practically by definition; however, not all distributed systems are decentralised. Large enterprises deploy distributed systems regularly and keep governance and decision-making processes centralised. Centralised systems suit those organisations where privacy, scalability, and access rights are major concerns. It is a commonly used system in environments where multiple remote users send requests to a server and receives individual responses. For instance, Wikipedia servers are mainly located around the Virginia region (USA), and clients can access their web servers anywhere [173].

The main characteristics of a centralised system are: the presence of a global clock, a single central unit, dependent failure of components, and only vertical scaling is possible. Some of the benefits of a centralised system include the easiness of securing it physically, its dedicated resources (memory, CPU) and maybe the best design option in some cases (e.g., cost-effectiveness, security). Some of the limitations of centralised systems include their high dependency on network connectivity, subject to abrupt failure, and fewer options for data backup; depending on the architecture, it can be challenging to maintain. Typical applications of centralised systems include application development (Django server, Express server), data analyses, and personal computing.

A decentralised system is characterised by the lack of a global clock, multiple central points, lower impact in the event of component failure (not compromising the entire system), minimal performance bottlenecks, high availability, more autonomy, and better control over resources. Each node controls its behaviour; consequently, the overall system has superior control over resources. On the downside, decentralised systems face higher complexities when realizing global tasks, the absence of a regulatory body, difficulty identifying which node failed, and a higher degree of difficulty in troubleshooting since many nodes can respond to a single request. Cryptocurrencies, decentralised databases, and blockchain applications are typical applications of decentralised systems.

Decentralised computing has become a trend in modern-day business environments. It offers many benefits over a conventional centralised system. It enables a trustless environment. It helps to improve data reconciliation, reduce points of weakness, and optimizes resource distribution. For instance, in a decentralised blockchain network, no one trusts anyone.

Blockchain model applications rely on some degree of centralisation. Thus, centralisation and decentralisation should be perceived as scales, not a single state—the more decentralised, the greater the independence from the third parties. In a way, decentralisation can be perceived as a solution to the centralisation problem. It offers an alternative solution by removing the need for powerful central authority and instead of spreading the control, tasks and responsibilities among the users. Decentralisation always invokes a decision-making mechanism reflecting a consensus on the level of trust among the participants.

In a decentralised network environment, nodes can make decisions independently, including systemic administrative and take corrective actions. All nodes are equal, nodes can join and leave. No permission for individual nodes to join the network is required. No single node or collusion of machines can overtake the system, and perform distinct actions that could compromise the entire network. When correctly designed, and to mitigate potential bad actors, decentralised consensus algorithms require the agreement of a significant proportion of peers, to reach an agreement across the network.

The traditional debate between centralised versus decentralised systems is around efficiency versus effectiveness. It is essential to establish a balanced solution leveraging a rationalistic strategy and trade-offs. The economics of computation, the requirements from stakeholders, constraints, and risks are decisions managers must consider before selecting the management option [174].

Figure 16 illustrates the evolution of decentralised computing since the Arpanet. Decentralised applications became popular in the software space after Napster, followed by Gnutella, FreeNet, and BitTorrent. It culminates with the introduction of Bitcoin in 2009 and Blockchain (2014-2015), which opens unlimited possibilities for deploying decentralised applications.

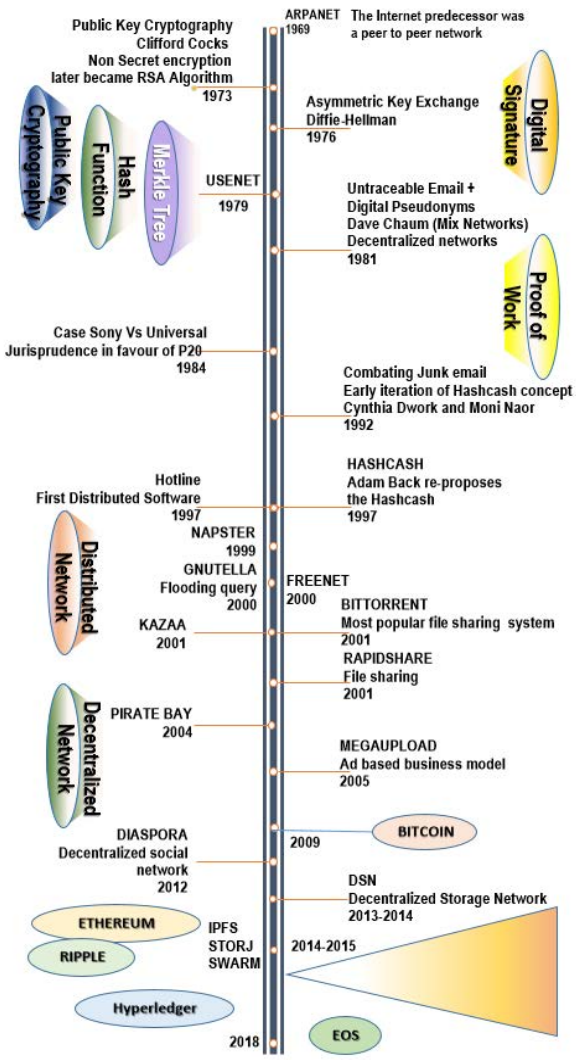


Figure 16- Decentralised computing evolution

Over the last decade, there has been an increasing number of security breaches. Private and public companies collect and control massive amounts of personal data in a centralised fashion that is supposed to be secure. In Dec 2017, the Identity Theft Resource Centre - ITRC reported a 45% increase in breaches compared to 2016 [175], and there is no indication the trends will slow down in the future. Alongside, there is a growing public awareness and demand for more reliable mechanisms for data protection. Decentralisation is one of the main driving forces behind the development of Blockchain – which has been asserted as a possible alternative to overcome the data breaching problem.

In a Blockchain context, decentralisation may refer to (i) the topology or physical arrangement of the nodes, (ii) the governance around the services and applications delivered, or (iii) the logical control that rules the entire system bringing together all network components through a consensus. The topological aspect (i) is related to several physical devices, how they are inter-connected, and how the system responds in case part of the network breaks down, a threat, or during an upgrade. The governance aspect (ii) of the decentralisation refers to the actual participants (nodes), the mechanics and conditions on how they control the system, how many, what proportion, what conditions, how trustful they are, or what type of decisions can be made and so on. Moreover, logical decentralisation (iii) refers to what piece of code, what version, and how the nodes respond as a single unity or individually.

Blockchain's governance and architecture are decentralised in the decision capabilities, and the nodes are away from a single location. The nodes' decisions and services are spread across many participants. On the other hand, it is logically centralised, as the entire system behaves like a single machine. All nodes act as a single unity, based on the same consensus protocol, holding a copy of the same ledger. Consequently, a node cannot censor another node or prevent individuals from joining the network.

The decentralisation aspects of Blockchain cover several demands: (a) it provides immunity against censorship; (b) increases availability and resilience of the system; (c) offers high fault tolerance; (d) creates a mechanism to share valuable data in a secure, tamper-proof fashion among untrusted nodes.

Decentralised networks are typically a subset of a larger group called trustless networks. As the nodes are all equal, it removes the trusting requirement that otherwise would be required by a centralised server. The negative side of deploying trustless networks includes interoperability issues since each Blockchain network has its specific protocols; governance problems since Blockchain has an open nature, making it harder to identify bad actors and remove them from the system; users may be exposed to different risks and not count with a security management system or customer support; users may lose passwords, hardware may become faulty; applications may have bugs, malware, files get corrupted – all these situations impose major challenges and must be considered when designing a decentralised system.

Network sponsors, developers or founders establish governance rules – and numerous decisions must occur during design and implementation. Block intervals, rewards, consensus protocol, and block size must be decided during the planning stage and may have to be changed or upgraded when the network is alive. There is no Blockchain network without an underlying governance structure. The degree of centralisation impacts network speed, throughput, reliability, and resilience. When an upgrade becomes critical during the operational stage, Blockchain stakeholders send requirements through *improvement proposals* similarly to any open-source application. Anyone can submit change proposals to the code base via the development team.

Although Blockchain runs on an open-source system intended to provide transparency, the decision-making process in a decentralised environment may have unexpected events demanding extra efforts compared to centralised systems. Different categories of stakeholders may have more influencing power on the development team. Upgrades and maintenance must comply with consensus rules. The user who submits a proposal for a source code change may not be able to capture the number of users voting. Users may not even know why and whether or not changes should be accepted. Some stakeholders may lobby in favour or oppose adopting a particular change. Most decentralised networks initially start with an egalitarian society approach. However, in a later stage, when problems surface requiring immediate interventions, this approach may be changed towards a benevolent dictatorship – or even a full tyranny approach. Measuring the levels of centralisation by checking at the codebase repository or by looking at specific sources is inherently limited [176].

E- CONSENSUS PROTOCOL

The absence of a central server and a governance authority in an untrusted environment calls for a genuinely reliable decision-making mechanism, namely consensus protocol. It is a collection of designed rules that participants (nodes) must agree upon to run the network consistently. This code contains algorithms, functions, procedures and actions representing the consensus rules. It enforces decisions among the nodes, solves network problems, and keeps the network running consistently. The consensus mechanism defines how to communicate and transmit data among nodes. It controls the flow of communication, task prioritisation, and continually registering the chain of events. It diagnoses hardware or software failures, bottlenecks, path redundancy, performance, network security, and bandwidth and ensures the smooth running of the network.

The consensus algorithm in a Blockchain is part of the source code, providing all the dynamics to the network functionalities. Task distribution, rewards (if applicable), transaction costs, punishment for misbehaviour, and system security are all embedded in the consensus protocol. Once a consensus status has been achieved, all the network nodes update their ledger simultaneously. Should any node tries to add or remove an entry to the ledger without reaching consensus, all the other nodes automatically reject the entry as invalid.

In a public Blockchain network, anyone with a suitable computer and a web connection can download the source code and participate in the Blockchain network. There are specific software packages depending on the type of network and category of nodes - such as light node, full node, or mining nodes. Mining is the process of executing a sequence of tasks followed by the creation of digital money as part of the rewarding scheme that the miner claims. Several miners compete to execute a sequence of tasks pre-defined by the consensus algorithms. The winner is the first to solve the computational problem, settle the existing block, and claim the rewards. The block mined is linked to the distributed ledger in the Blockchain network. The winner creates a new block of transactions and starts mining again, entering a new competition. The consensus protocol determines what the miners are responsible for, how transaction validation occurs, and when to create the new digital cryptocurrencies as part of the rewarding scheme. The mining activity became a business with several multi-million dollar organisations specialising in this space.

There are dozens of consensus protocol types across several hundreds of Blockchain active networks, and always a trade-off when selecting the consensus protocol. Each consensus algorithm uses different approaches to target specific problems and objectives. The design reflects technical and business requirements defined by the Blockchain project's strategies. Some solutions prioritize features such as anonymity, transaction time, and transfer costs, while others focus on usability, performance, or security. Popular implementations are the Byzantine Fault Tolerance (BFT), Proof-of-Work (PoW), Proof-of-Stake (PoS), and Delegated Proof-of-Stake (DPos).

- **Byzantine Fault Tolerance (BFT)**: is a highly technical and popular communication protocol family with several hundreds of variations. It was first introduced in the early 1980s and had hundreds of variations [177, 178]. Modern BFT state machine replications versions may have 20,000 lines C++ code [179]. BFT is built around the Byzantine generals' problem. The BFT consensus algorithms typically employed in the cryptocurrency environment allow generals (validators) to control the state of a chain by sharing messages until it reaches the expected destination, with the correct transaction history and guarantee of consistency. It has a centralisation component; therefore, it favours some types of applications while being considered a drawback for others. BFT allows scalability and lower transaction costs. Ripple implements BFT, and the validators are pre-selected by the Ripple organisation. Stellar also implemented BFT, trust is established by the community, and anyone can be a validator.

The Byzantine general's problem refers to a consensus formation problem among the generals during the Byzantine Empire. A group of generals, each one coordinating an army division, want to attack a city but they face two issues: (a) their armies are far apart making it impossible to elect a centralised authority and organize a coordinated attack. And (b) the city has a strong army and the Byzantine generals only can succeed if they all attack together at once. On top of that, there could be traitors, spies, messages could get corrupted or not arrive on time. There are several approaches to solving the problem. The solution combines trust, incentive and punishment mechanisms where all generals are led to a single decision. They could all retreat or attack, always as a group.

- **The Practical Byzantine fault-tolerant (PBFT**) model is an extension of the BFT consensus. Every node distributes a public key. All nodes are ordered in a sequence, with one node being the primary node (leader) and the others being the backup nodes. Messages getting through the node confirm its organisation. PBFT is designed to work in asynchronous systems and is optimised to be high-performance with a notable overhead runtime and low latency. This concerns digital resource-based platforms that do not require high throughputs, although it is capable of numerous transactions. Trust is decoupled from asset possession, making it feasible for non-profit and small organisations. Hyperledger Fabric and Ziliga currently utilize PBFT.
- **Proof-of-Work (PoW):** This protocol has been deployed on many Blockchain and was the first successfully decentralised Blockchain consensus algorithm. PoW is currently used by all the mainstream cryptocurrencies such as Bitcoin, Ethereum, Litecoin, ZCash, Monero, and many others. All the miners compete to add a collection of valid transactions and form a block. The winner will append this block to the global Blockchain network and be rewarded an established number of coins. The amount varies according to the consensus

rules. To generate a successful block, the miner undertakes to solve a computationally-intensive problem; however, the verification process is straightforward. The miner hashes all the candidate transactions, picking the most attractive ones in terms of size, complexity and financial returns - and then forms a hashing Merkle tree [154], generating a digital signature scheme for the entire block of transactions. Next, it calculates a nonce that, combined with the Merkle root hashing, generates a specific output containing an initial sequence of zeroes dictated by the consensus algorithm. The number of zeroes determines the degree of difficulty imposed by the algorithm, and this property is adjusted periodically according to the network performance needs. Finding the right nonce computed together with the resultant of the Merkle tree hashing is the actual quest, the proof of work that gives names after the protocol (PoW). It requires huge mining processing power, measured in the number of hashes per second. The current Ethereum Network Hash Rate (Q2 2022) is 1,029.23 TH/s, while Bitcoin Network Hash Rate is 197.53M TH/s [164].

PoW has been successful over several years and efficiently against Denial of Service (DoS) attacks. On the downside, PoW has several limitations, including high power consumption, low transaction throughput, high transaction costs and being environmentally unfriendly. The formation of mining alliances that can lead to selfish mining is another concern [180, 181], along with poor scalability, transactions cost (financially and computing), and debatable network security. For instance, the 51% attack, or the majority attack, occurs when malicious cryptocurrency miners take control of the tokens' Blockchain [182].

- **Proof of Stake (PoS):** PoS is a class of consensus algorithms for public Blockchain, with many variations. The first Proof-of-Stakes (PoS) network, Peercoin [183], was developed as a PoX consensus mechanism to reduce the computational requirements of PoW. The two main types are (a) chain-based proof of stake and (b) Consortium based on BFT style. For the chain-based proof of stake (CBCPoS), the algorithm pseudo-randomly chooses a validator throughout each time slot (e.g., 10 seconds). It is specifically intended to select validators so they can always include transactions with minimum delay [184]. It delegates to the validator the option to create a new block and must point to the previous block of the longest chain. Most blocks converge into a single, constantly growing chain, which occurs over time. The Robust Proof of Stake (RPoS) consensus protocol has been proposed by [185] which uses an amount of coins to select miners and limits the maximum value of the coinage.

As for the consortium BFT-style proof of stake, the validators are selected at random, with the prerogative to suggest new blocks. Nevertheless, deciding on which block is official is only achieved by a multi-round process where all validators vote for some specific block during each round. All validators must agree if any given block shall be part of the chain or not. The algorithm design determines specifically how the mechanism shall work. The blocks may still be chained together; however, the consensus can be reached faster within one block, independent of the length of the chain.

PoS requires nodes to risk part of their gains to verify transactions. Instead of mining to solve complex computational problems and verify and group transactions, miners stake their assets on transactions by locking up coins. If the PoS miners pose illegitimate transactions, the consensus protocol would have their stakes dropped. The miner selected to complete the block is often selected in proportion to the value they have at stake in the network compared to the total value of the network. Contrary to PoW, PoS discourages bad behaviour by shifting verification to those with the most value bundled up in the network. The benefits of PoS are that (a) it is more energy-efficient compared to PoW and (b) a lower number of coins to motivate participants in the network. (c) It opens new possibilities for game-theoretic mechanisms to better discourage the formation of miners' cartels. Nevertheless, PoS has not yet been proven effective in a major scale project. Its performance is still untested in several scenarios. Dash, Redcoin, PIVX, and Navcoin are some cryptocurrencies that currently use PoS. Ethereum Foundation announced several plans to move to Proof-of-Stake sometime in the future.

- **Delegated Proof-of-Stake (DPoS):** as an alternative to risking coins to validate transactions, DPoS token holders vote for a select group of nodes to perform the validation role. In a sense, DPoS remains decentralised as there is no static central management. All the nodes participate in the selection process for selecting which node(s) shall validate transactions. Depending on how DPoS is designed, it has a centralised component, so a smaller group can make decisions. This improves performance, transaction and verification speed. DPoS implementations maintain a reputation, ongoing voting process, and rearranging system that stimulate elected validators to remain accountable and honest. The benefits of DPoS are scalability and faster transaction verification. Conversely, the disadvantage is its partial centralisation nature, and the governance model, which has not been proven effective in a large project.

Newer consensus algorithms have been proposed regularly. Besides the mainstream protocols, there are several hybrid versions and auxiliary solutions focused on solving specific limitations of Blockchain.

F- Software Development

The Blockchain stack can be split into the physical layer, platform, distributed computing network, and applications. The physical layer holds the infrastructure, all the node machines, network facilities, data storage, power backup systems, ancillaries and more. The nodes are the machine participants (or peers), with the hardware components required to run the blockchain. A typical blockchain network has light nodes, full nodes for verification or validation and mining nodes for block formation and rewards. A light node is the simplest type, and can only send and receive transactions, keeps no records of the ledger, and cannot validate transactions.

Conversely, a full node holds a copy of the latest state of the ledger and can validate transactions. A mining node has the same full node capabilities but can generate new blocks. The storage unit keeps the ledger of the transaction records, and the increasing transaction data records reflect the processing time and require more storage space. The platform layer accounts for remote procedure calls - RPC [186], web application programming interface - API, [187], and REST APIs [188] for communication among peers. The distributed computing layer guarantees local access to the data, immutability, authenticity, privacy, network security, and fault tolerance. The

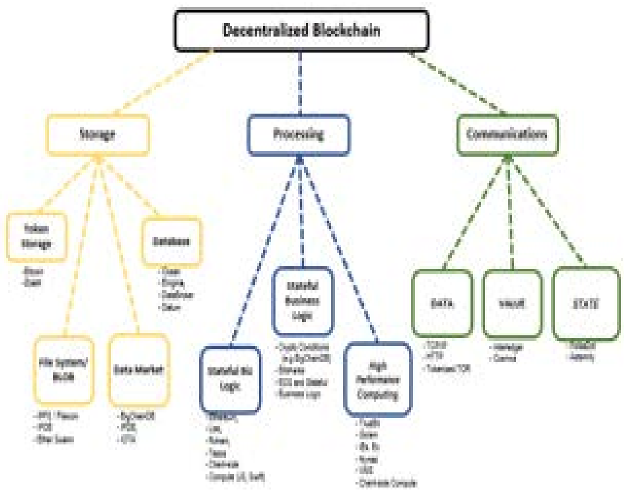


Figure 17 – Blockchain Infrastructure Software Landscape

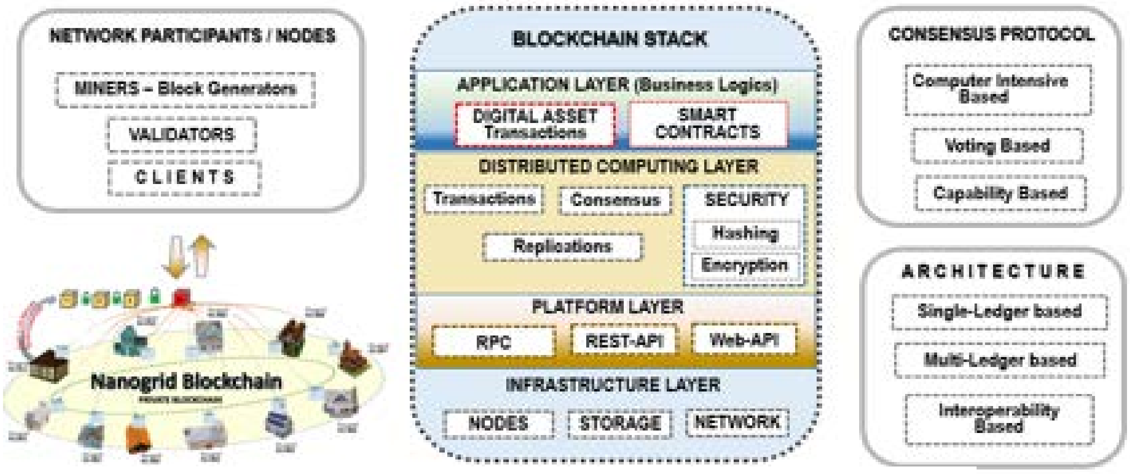


Figure 18: Blockchain Stack

miners enter a competition to solve a mathematical quest, and the winner can order the transactions and generate a block according to the consensus rules. In addition, the distributed computing layer is accountable for user authentication, data integrity, provenance, traceability, and privacy – by using a hash function and encryption [189, 128]. The application layer houses the business and strategy logic, digital assets, historic transactions, and *smart contracts*. Figures 17 and 18 shows a conceptual early version of the blockchain platform software stack.

Besides serving as a platform to send and receive digital money, enabling the creation of crypto-tokens, Blockchain also offers a framework to implement *smart contracts*, deploy decentralised applications (DApps), and serve as a business platform to raise funds. So, the three main trends in Blockchain are cryptocurrencies, DApps and business platforms. These three segments are linked – or not, depending on the Blockchain solution. A new startup may not need Blockchain as a digital ledger technology and still benefit from Blockchain as a business platform. In that case, Blockchain allows the implementation of tokens in replacement of equity shares in crowdfunding so that assets can be raised via an Initial Coin Offering (ICO) and reach a much larger audience. Alternatively, a company might develop a DApps using a Blockchain platform, so the product can be quickly launched and enter the market much faster than traditional solutions.

There are three paths to create a new cryptocurrency: (a) developed out of an existing open-source core Blockchain code and then customised as per requirements, (b) forked out from any existing Blockchain network and then customised, or (c) the code can be re-written from scratch including new features and targeting specific market niches.

During the start-up process, tokens can be created for ICO, STO and ETOs. Decentralised computing systems involve storage, processing and communications, and specific Blockchain technology must be tailored for each blockchain network. There is no "*one technology fits all*" solution since different development platforms present different benefits and limitations.

Crowdfunding raises finance by reaching a large population or organisations to acquire equities (or prizes) and uses the Internet to find millions of potential investors [190]. The concept of crowdfunding has been expanding, adapting, and enabling a plethora of innovations. It can be deployed in projects, services, development of new products, investments, causes and experiences, triggering a change in financial institutions' roles. As crowdfunding became a mainstream investment option, hundreds of crowdfunding organisations have emerged worldwide [191].

Ethereum framework enables the implementation of *smart contracts*, which are methods or functions running on the Blockchain. Every time a *smart contract* is executed, the execution takes place in the Blockchain, then registered permanently in the ledger as a transaction. *Smart contracts* for Ethereum Blockchain are written in *Solidity,* a contract-oriented code influenced by C++, Python and JavaScript and designed to target the Ethereum Virtual Machine (EVM). Bitcoin uses stack-based programming, which is not Turing-complete. Although effective for token distribution, it presents limitations for *smart contracts.* The Ethereum platform also enabled the creation of *Decentralised Autonomous Organisations (DAOs*).

BigchainDb addresses the scalability problem of Blockchain. Scalability can be a significant challenge for any Blockchain network, and storing a large amount of data shall always be avoided. BigchainDB is a Blockchain-related technology that could also be used in a stand-alone mode. It can provide high throughput, e.g., 1 million transactions per second. It can also be used in conjunction with Ethereum to act as a secure Blockchain database where Ethereum acts as the logic processing part of the stack. The development of BigchainDB through nodeJS or various other programming languages [192].

2.3.2 Major Roadblocks for Blockchain Technologies

Blockchain may become a viable choice for applications needing process improvement, tracking data, process automation, and ensuring provenance and accountability. It can also serve as a payment rail, a business platform for launching decentralised applications (DAPPs) and decentralised autonomous organisations (DAOs) and help startups in new joint ventures. Among the major technical barriers to the widespread adoption of Blockchain technologies are scalability, performance, feasibility, high complexity, security, maintenance constraints, and the impact on the environment.

Specifically to cryptocurrency, there is the absence of customer services, the risk of compromised private keys, the high complexity, software failure, and the introduction of intermediaries. The risk of software or hardware failure. On an application delivering a video, this may not be a problem. However, in a Cryptocurrency market, if the user loses the password or token, all the assets can be lost for good. Apart from technical constraints, other major roadblocks are:

Regulation: Blockchain users are spread across financial, healthcare, government, energy industries, and many others. These sectors are heavily regulated, bringing challenges and opportunities to the sector. In many cases, Blockchain applications may fall into the grey area, which the regulatory bodies do not cover or define. It is expected that when blockchain technology matures, its adoption across various sectors may increase even further. Lack of regulation leads to interoperability among different vendors and unclear running costs [193].

Lack of Clarity: the underlying complexity of the Blockchain becomes a barrier since most decision-makers still do not understand the advantages, business potential, and the many use cases and technology available. Identifying needs and developing tailored solutions require in-depth skills on the technical and business sides. Short- and long-term adoption, deployment, and usage benefits are still unclear. The benefits of Blockchain may only be realised over the next decades when the learning curve for business is over and strategies are better defined [194, 195, 196]. Some paradigms around clarity include: establishing a reliable discourse that benefits the community and the environment, raising public awareness, training programs, interoperability, and selecting the most efficient blockchain solution to meet stakeholders' expectations [197].

Governance: Blockchain evangelists promote openness, freedom, transparency, and trustless systems, with no safeguard, or standards. Who will be auditing the code to prevent fraud five years from launch if a back door is maliciously built-in somewhere along with a 60,000 lines code? There are many grey areas and several challenges. *Smart contract*s and complex agreements can be hard to map to the natural language with hardwired code.

Therefore, manual intervention or the inclusion of third parties becomes necessary. Since *smart contracts* are not legal agreements, it becomes paramount to create technology capable of linking computational transactions to traditional contracts and ensuring law enforcement [198].

2.3.3 Blockchain Applications in the Energy Environment

Decentralised renewable energy systems, energy trading platforms, and power plant cooperatives have been investigated intensively and are becoming hot topics [199]. However, integration requires controls and supervision, which, in the electricity context, is traditionally provided by power utility companies. Service providers measure the amount of electricity consumed and the key performance indications, such as power availability, power cuts, quality, voltage levels, power factor, availability, frequency, and harmonics. The focuses are on customer satisfaction, economics, operation and production costs.

Blockchain applications in the energy sector are emerging, and it has the potential to transform the energy segment. Several frameworks are being proposed to secure consensus in Blockchain-IoT applications [200, 201]. Typical applications include peer-to-peer energy trading, network management, certification of CO_2 footprint, and information security systems. Energy crypto tokens for energy trading are promising [202, 203, 204, 205, 206, 207, 208, 209, 210], and several innovative approaches have been brought forward [211, 212]. Some projects have been successfully implemented [213, 214]. [215] assessed current trends on deploying blockchain coupled with IoT in the energy sector to solve privacy and security aspects and discussed potential solutions to these challenges.

Blockchain has also been proposed to facilitate the implementation of GHG emissions (footprints) inventories, keeping track of the impact related to the supply chain, and the Global Value Chain (GVC). The multiplicity of suppliers creates high complexity on traceability and provenance. A Blockchain-based application can address all those problems by tracking product history records [216], and provide decentralised management without the involvement of a formal (third party) authority.

Community integrated energy systems (CIES) [217], Green-Smart community-integrated energy systems (GreenSCIES project) [218], and integrated demand response (IDR) [219], are all propositions within power plant communities. They seek to enhance operational aspects, increasing the system's flexibility, improving utilisation efficiency, and enabling variable loads, power conversion, and energy storage systems on the power load side.

An energy transaction platform based on Blockchain technology using IDR has been presented by [219]. A Crypto-Trading project exploring the unique capabilities of Blockchain, integrating *smart contract* functionalities to share energy and managing integration among several householders has been presented [220]. The crypto-trading project implemented a modular Blockchain-based software system linked to cryptocurrency exchanges and focused on the renewable Energy Market. It deployed a robo-advisor capable of making suggestions to prosumers on the best-selling option [220].

Privacy is crucial when performing power-sharing, bartering, or trading within communities. Several approaches have been presented to solve the confidentiality, traceability, provenance, and trust aspects [221, 213, 222]. [223] suggested a model for privacy-preserving energy scheduling based on the energy Blockchain network. The solution deployed Lagrangian relaxation and *smart contracts*. [224] presented a Blockchain-based P2P energy trading platform providing simulation results, calculating and comparing the economic benefits. Using Industrial Internet of Things (IIoT) technologies, peer-to-peer energy trading has been achieved.

However, when crypto payments are involved, frequent transactions can yield very high operational overhead costs. To solve this problem and reduce overhead costs, [225] proposed a scheme enabling nodes to meet the power demand through a local energy system. In that case, a node must be self-sufficient before joining the network as a seller, considering the prosumer have a sufficient surplus of energy. [226] suggested a Blockchain-based authorisation scheme responsible for power supply management and power transaction. The implementation allows superior monitoring, control and user authorisation functionalities. Moreover, it enables secure access to power supply and storage and delegation of control among peers. Latency and scalability are major concerns for Blockchain solutions. The trade-offs between privacy and speed are challenging since one undermines the other. Higher privacy requires more access control, inputs, and variables, and naturally, it impacts performance, extra time for processing, and precautions against tampering.

Blockchain models for the energy sector have been deployed in several start-up ventures worldwide, such as LO3 Energy (USA), Power Ledger (Australia), Electrify (Singapore), and WePower (Estonia), to mention a few. Around 2019, 140 Blockchain research projects and start-ups were identified with potential applications on Blockchains for energy [36].

2.4 IoT

The term “Internet of Things” was coined and published around 1985 by Peter T. Lewis in a speech to the Congressional Black Caucus Foundation in Washington, D.C. [227]. In his original words, Mr Lewis’ put forward: “*I predict that not only humans, but machines and other things will interactively communicate via the Internet. The Internet of Things, or IoT, is the integration of people, processes and technology with connectable devices and sensors to enable remote monitoring, status, manipulation and evaluation of trends of such devices”*. Four decades later, the concept of IoT is still evolving, and definitions are still uncertain.

IoT refers to the interconnection of hardware or software devices, automating tasks and processes for households and industrial applications. IoT technology may enable the control of mechanisms locally or remotely, monitor and supervise the performance of systems or components, remote access management, data acquisition, transformation, or transfer. Any event detected, electrically, mechanically, or logically, can be digitalised and transmitted through the Internet – or via a local network.

Wireless sensor networks (WSN) started in military applications in the 1950s, long before IoT. According to [228] the deployment of wireless sensor networks enables the “*connection among the physical world, computer world and ternary world of human society*”. Sensors can be interconnected in different topologies, depending on their types and features, and then linked to a hub that re-transmits the data to a server. Various communication protocols support WSN, depending on the application, e.g., satellite, LAN, LoRa, and many others. WSN overlaps with IoT in many aspects; however, IoT marketing evolved and became prevalent – although there are some misconceptions, and IoT can be seen as a misnomer. IoT interconnects smart devices, objects, and machines to the Internet. There must be transmission media, communications protocols, hubs, and sensors. So, IoT per si does not exist without a traditional infrastructure. On the other hand, a WSN can interconnect sensors to a hub and re-transmit the signal to remote locations without using the Internet.

There are many options when interconnecting devices depending on the application, project requirements, environment, and constraints. Wired and wireless communications have been deployed for over a century, and specific industries include telecoms, power supply, oil and gas, building automation, railways, and space agencies (e.g., Nasa).

IoT and WSN are widely deployed in control systems, such as building automation, environmental monitoring, healthcare, smart building, transport, surveillance, robotics, learning agents, malware detection, disease detection, agriculture, and military. Sensors play an important role in creating solutions using IoT technologies.

Sensors are devices that detect external information and convert it into a signal. It can detect the state of a device, take a periodical measurement or when triggered by a certain threshold or state (e.g., temperature, vibration, location, voltage, current) and then relays the data to a hub, microprocessor, or server. Data aggregation from multiple sources and real-time analyses to produce meaningful information and support informed decisions can be complex. [229] addressed data processing techniques through "*denoising, data outlier detection, missing data imputation, data aggregation, feature extraction and integration with emerging technologies*".

Wireless sensor networks (WSN), remote actuators, microprocessors, and embedded systems existed long before IoT. However, IoT simplifies the integration, enabling a comprehensive range of devices to be interconnected via the Internet. IoT addresses the compatibility problem among vendors, proprietary protocols, features, and models, allocating different devices under a single framework. Before IoT, only large institutions could do it, requiring substantial resources and skills.

Popular IoT protocols include Zigbee, Z-wave, LoRa, LoRaWAN, LPWAN, Bluetooth, BLE, and 6LoWPAN, and all can be connected to a processor via Wi-Fi, 4G, 5G, and many other communication protocols. Again, IoT is still evolving in several directions, industrial, smart cities, home automation, building automation, health, and many more.

Once integrated under a single platform, it can enable many other features depending on the application field, such as task automation, interoperability between objects or machines, network and device monitoring, controlling, data recording, broadcasting real-time events, timestamping, and many more. It may be integrated with other enabling technologies for analytics, statistics, and forecastings, such as Big-Data, Machine Learning, and cloud computing. It can significantly facilitate feedback and interactivity with users.

IoT technologies can help to improve productivity, enhance operations management and lead to better resource and asset management. During downtime periods, automatic scheduling can help to reduce operational costs. Work safety can be improved, leading to better opportunities for production to be scaled. On the downside, there are environmental concerns, privacy, and security – besides complexity.

Market penetration of IoT technologies has continually been growing, although far below media projections making it difficult to separate the publicity from the facts [11, 12, 13]. Most applications are linked to task automation, boosting production, lowering costs, and increasing business. Without improving production methods to avoid environmental impact, it can be questionable if IoT would be helping the vendor and users in the short term – and depleting the planet faster in the long term.

2.4.1 IoT Applications Within Energy Sector

Green IoT focuses on reducing GHG effects on the environment and maximising the energy efficiency of IoT devices [230, 231]. Green IoT has also been proposed in Green-RFIDs, Green-datacentres [232], and Green-cloud computing [233, 234]. Balancing energy consumption by using the Green IoT concepts in cloud applications has been discussed by [235]. A decrease in power consumption by sensors and intercommunication was described in [236], although the overhead transmission among sensors can create extra delays in data communication.

IoT application for interconnecting multiple organisations via a hybrid-Blockchain (H-chain) network, using a software-defined network (SDN), has been proposed by [237]. The authors suggested a rewarding scheme to address power consumption control by motivating.

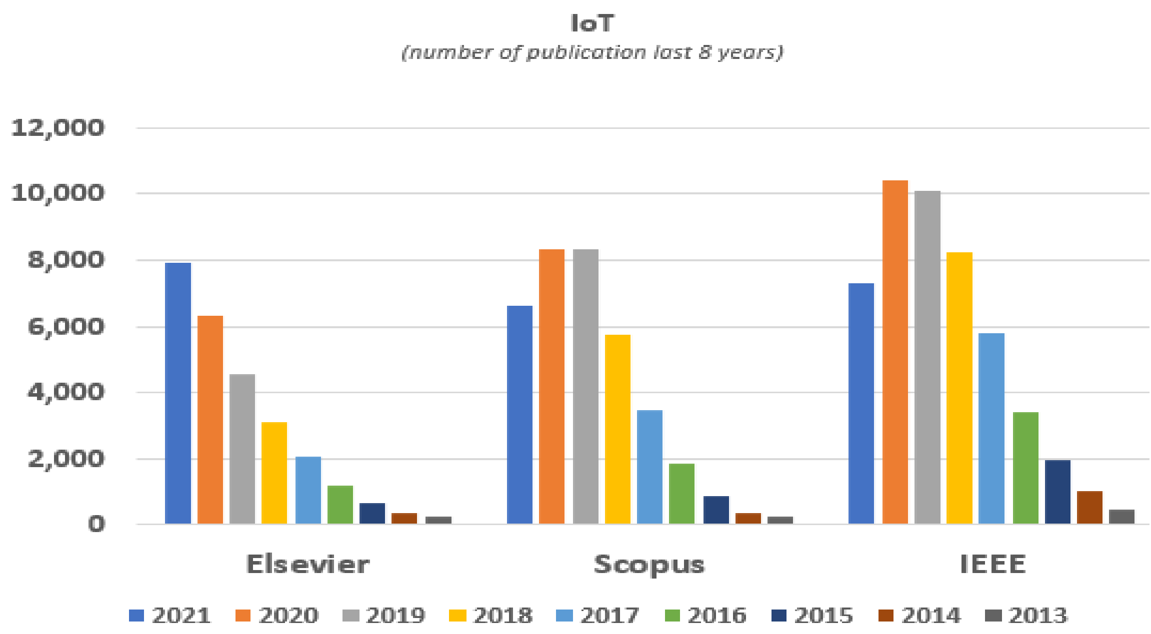
Power consumption disaggregation for individual loads by deploying non-intrusive load monitoring (NILM) solutions have been proposed by many vendors. A single sensor is installed at the entry phase at the switchboard, and IoT-AI agents can learn patterns, disaggregate signals, and recognise an appliance. The market options available for home energy monitoring systems using NILM technologies can be overwhelming. Typical vendors include Emporia Vue Smart Home [238], Powerpal [239], Smappee Infinity [240], TED Pro Home [241], Egauge [242], Efergy [243], Sense Energy Monitor [244], and many more.

[245] presented a study on the state of the art of ML models deployed in energy systems followed by a narrative of the taxonomy of AI models and applications, while [246] proposed a power monitoring model used to generate the training data and alleviate the need for historical data of the appliance. It uses IoT components to support observable states to the disaggregation model to enhance performance. A "*selectively enabled factorial hidden Markov model*" is applied in which states of IoT control relays are presented to the model. The solution enables control of appliances, monitoring, and offering insights over consumption of energy and power load disaggregation.

[247] presented an outlier detection system for measurements extracted from IoT platforms. The author used a scheme to validate the detected values through a coefficient of determination analysis and applied a combination of a bi-square algorithm, weighted-least square (WLS) and robust fit.

IoT technologies have been proposed to lower energy consumption and CO_2 emissions, supporting a more sustainable environment. [248] through a small-scale energy trade model between a power producer and a buyer in a peer-to-peer (P2P) environment. The model makes use of a virtual prosumer control system through the power grid in real-time and does not rely on an energy storage system (ESS). Therefore, the gains of energy producers

Figure 19: Number of Publications on 'IoT' over the last eight years



and consumers are maximised, enabling an increased financial gain, and a sophisticated demand management system. [249] suggested an energy disaggregation model using an *"energy demand supported by an IoT-based control"* capable of monitoring loads non-intrusively, by using a single energy management system (smart meter).

The trend in academic IoT publications has been significant for eight years (Figure 19). The rise in interconnected devices impacts system complexity, making it challenging to manage and control the flow of information in real-time. Modifying networking rules while ensuring changes do not break the service continuity becomes risky and time-consuming.

Node-RED system has been proposed as mitigation to this limitation as it allows the introduction of new features [250]. Node-RED is a visual-based code editor that works on the browser. Its version 2.0 release in 2021 works on Node.JS 12.17 or later., which is a flow-base, open-source, JavaScript-based tool. Node-RED was conceived and built by IBM Emerging Technology as part of a portfolio for online services [251]. It facilitates the integration of IoT hardware, from multiple vendors, and firmware versions, easing the development of APIs (Application Programming Interfaces). As self-explainable, Node-RED is built with nodes, which are graphical representations in the shape of a small rectangle. There are several classes of nodes with specific functionalities, properties, and icons. It works in a drag-drop fashion, allowing the wiring up of multiple nodes. Nodes and scripting codes (e.g., Python) can be imported and exported to and from other sources, projects, or repositories (e.g., Github, Sourceforge, Bitbucket, etc.). Node-RED eases the deployment of devices and flows using the wide range of nodes in the palette that can be deployed to its runtime environment, making it suitable for rapid development, testing, prototyping, simulation, modelling, and shortening the time to market.

Advanced Message Queuing Protocol (AMQP) and Message Queuing Telemetry Transport (MQTT) are both Machine-to-Machine (M2M) protocols widely deployed in IoT environments. MQTT has a client-broker architecture, MQTT follows the publishing-subscribing scheme, and its header size is limited to 2bytes, while the message body size is small and defined. On the other hand, AMQP has a client or broker and client or server architecture [252] and adopts a request-response approach as well as publish-subscribe methods. its header size is 8bytes, and its message size is larger, negotiable and undefined [253]. Whereas AMQP uses SCTP for communication and IPSec, TLS, SASL, or SSL security standards, MQTT only uses SSL or TLS. The QoS offered by MQTT is the "*fire* *and forgets*” format when the Quality of Service is 0. At least one if QoS is ‘1’ and precisely one if QoS is ‘2’. On the other hand, AMQP’s QoS is to “*settle and unsettle”* mode, which is analogous to MQTT [254].

2.5 ARTIFICIAL INTELLIGENCE (AI)

Around 1948, computer machines could execute instructions but not recall the functions or methods deployed. There was no memory, nor history of events. Alan Turing developed a computational model that defined an abstract machine capable of manipulating characters on a strip of tape corresponding to a rule (decision) table. Given any mathematical equation written in machine procedure language, a Turing machine can implement the logic, and execute the algorithms [255]. In 1948, Alan Turing wrote an essay, "Intelligent Machinery", discussing how to build intelligent machines. In 1950 Allan Turing tested this intelligence and presented the paper “Computing Machinery and Intelligence” [256]. Around 1955, the first AI application was demonstrated at the Dartmouth Summer Research Project on Artificial Intelligence (DSPRAI), which became a reference point for AI research [257, 258].

In the early days, AI-enabled computers played games like checkers against humans. Gradually, processing speed became faster, AI algorithms improved, and new applications emerged. In 1997, Deep Blue was the first chess-playing application to beat the world chess champion, Garry Kasparov, [259]. Around the same time, earlier versions of speech-recognition applications were built by Dragon Systems, on Windows operating systems. More recently, Kismet, a robot that can recognize and display emotions, was presented by Cynthia Breazeal [260, 261].

AI refers to machines capable of reading data, perceiving the environment, and taking action to achieve a specific goal. It analyses data to enhance the potential of achieving desired outcomes. It may derive information to support problem-solving, decision-making, creating recommendations, and automation. A broad range of software tools can mimic and even exceed human intelligence. AI can be a system built through knowledge representation capable of reasoning and problem solving, a technology, an engineering science, or any process capable of learning, self-improving, perceiving an environment, and taking actions towards maximizing its chance of achieving its goals.

The front value benefits of AI can be related to time savings, task automation, user experience enhancement, comfort, easy living, facilitating daily chores, and more. AI can provide a scientific method to test applications. Scientists can evaluate, compare or even blend distinct methodologies to isolate a problem. Agents can enquire, simulate, and exploit the best solution for a given task. It enables a common communication language that is used in many fields — such as statistical optimisation or economics [262].

The liabilities for AI technologies have not been adequately addressed and are still miscomprehended by the public. The dominant applications are primarily for business, and ethical concerns have been raised [263]. AI technology has been poorly presented to society, often aiming to convince the outside world of its success rather than engage in assiduous self-criticism in the physical sciences [264]. The privacy aspects, human behaviour changes, and excessive exploitation of technology to elicit acquisitions of new goods and services increase business, despite the negative consequences for the young people, future generations, and the planet.

The correlations between the growth in consumption, the rise of emissions, global warming, and extreme weather have been well established among climate change scientists. As put by the illustrious physicist Stephen Hawking: "*Success in creating effective AI could be the biggest event in the history of our civilisation. Or the worst. So, we cannot know if we will be infinitely helped by AI or ignored by it and sidelined, or conceivably destroyed by it"* [265].

AI technology may include agents that classify, analyse, draw predictions, learn from the historical data, act on it, improve its quality, sense the environment, and respond in the present. The key difference with other state-of-art technologies is that AI has an infinitely more extended reach, far beyond the scalability problem. AI touches on fundamental questions about science and human existence. It opens up the introduction of super-intelligent machines that could be subtly programmed for social manipulation, privacy invasion, and a wide range of social grading. It can provide powerful tools to support humankind and nature if well deployed. The responsibility for educating people on the risks, benefits and liabilities of AI has been left to the second plan.

The AI scoping for applications and goals has been continually expanding. Business sectors using AI technology include healthcare, automobile, banking and financing,

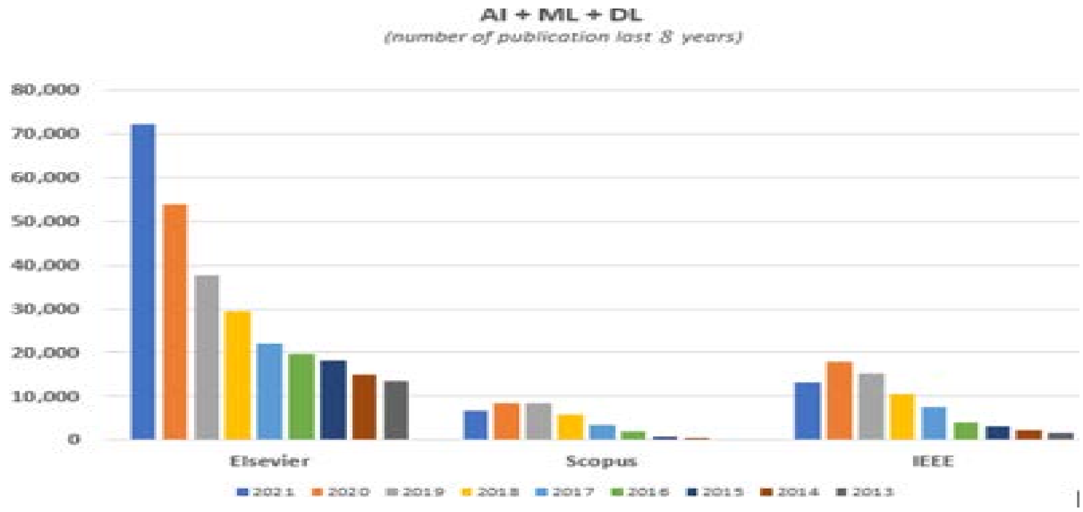


Figure 20: Number of Publications In AI, ML, DL over the last nine years

surveillance, social media, entertainment, education, gaming, e-commerce, robotics, agriculture, and many others. Typical applications involve advanced web search and optimisation tools (e.g., Tensor Fire, Chrome, Firefox), the logic for knowledge representation (KR) and problem-solving (e.g., GraphPlan, Satplan Black Box), recommender engines such as those used in e-commerce (e.g., eBay, Amazon), video streaming (YouTube, Netflix), facial recognition (Betaface, Cognitec, Amazon-Rekognition, BioID, Face++), human speech (Polly, Linguatec, Capti, NaturalReader, Siri, Alexa), autonomous vehicles (e.g., Waymo, Uber ATG, Toyota e-Pallete, APTIV, Tesla autopilot), automated decision-making, competing at the highest level in strategic game systems (e.g., chess, DOTA2, and Go). The use of AI to automate (or enhance) research has stirred debates within academia, including management [266], biology [267], and health sciences [268, 269].

The difference between AI technology and traditional programming is that regular programming identifies all possible scenarios and operates only within those boundaries. Conversely, AI 'trains' an algorithm to execute a specific task, allowing it to further explore, learn and improve on it. Optical Character Reading (OCR) technology, widely deployed in image scanners, is not recognised as an AI technology since it cannot improve on its own; however, facial recognition software is capable of identifying faces, given a substantial amount of data is available. A typical AI system should be able to acquire and interpret data from the surrounding environment, point out when similar occurrences occur, or make recommendations towards achieving the desired goal.

Similar to IoT and Blockchain, the AI field remains largely unexplored, and predictions are merely speculative. The trend in academic AI publications has been growing exponentially (Figure 20).

2.5.1 Types of AI

AI aims to program machines to mimic human-like functioning to maximize outcomes for stakeholders. How machines can be compared to humans in terms of versatility and performance, permits several AI classifications and is perceived as the computational capacity of the human brain as a physical system [270, 271]. In short, the extent of the capability of an AI system to mimic or replicate human abilities defines the types of AI.

AI can be classified according to its functionality or similarity to the human brain and its ability to interact, sense the environment and context, and respond according to each situation. Another method is to organise the AI system by its technological capabilities. As for functionalities, there are four types of AI or AI-based systems: (a) reactive machines, (b) limited memory machines, (c) theory of mind, and (d) self-aware AI. Moreover, classification by technological capabilities yields three types: (e) Artificial Narrow Intelligence (ANI), (f) Artificial General Intelligence (AGI), and (g) Artificial Superintelligence (ASI). Figure 21 and Figure 22 show AI classification by functionality and technology, respectively.

(a) Reactive Machines

These are the primary form of AI systems, and when given a category of information, the system reacts in a mapped fashion. There is no actual learning activity happening anywhere within the system - as the machine mimics the human brain's ability to respond to events automatically. A system that takes a human face as input and outputs a box around the face to identify it as a face is an example of a reactive machine. It emulates the human mind's ability to respond to stimuli without recurring historical data, like the

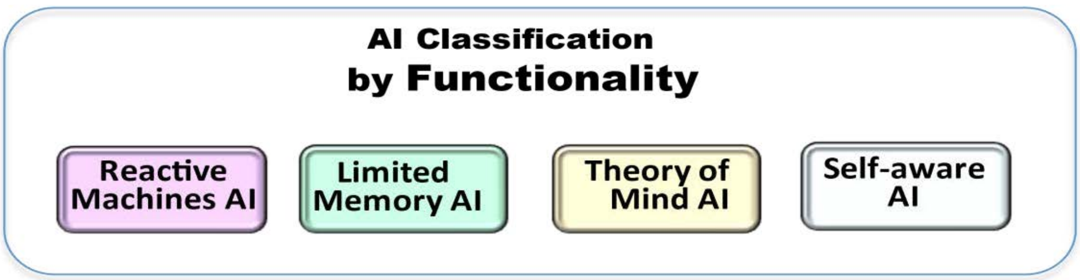


Figure 21: AI by functionality

fight or flight response by the sympathetic human nervous system. Static machine learning models are trained offline and are typical examples of reactive machines. On the flip side, a dynamic model is trained online, as data feeds the system continually and updates the model.

Reactive machines are given specific tasks and only respond to pre-programmed scenarios, which is helpful in applications such as robots playing a game (e.g., chess against a human). Reactive systems can only automatically respond to limited inputs or combinations. They cannot be used to rely on memory to improve their operations based on the same. Reactive machines can work with maps and other forms of pre-planning altogether and focus on real-time environment observations. [272] proposed the *statechart* method in 1985 to find a satisfactory method for behavioural description and concluded that concurrency might occur in both dimensions, as orthogonality of states in one and as parallelism of subsystems in the other.

The IBM chess program that beat the famous world champion in the 1990s is an example of reactive machines [273]. AlphaGo from Google defeated a top human Go player, an accomplishment that recently perplexed scientists [274]. It used a neural network to watch developments in the game and respond accordingly. Although remarkable, the system does not interact with the world and only reacts to the same situations in the same pattern every time those scenarios come across.

(b) Limited Memory

In addition to reactive capabilities, limited memory machines can learn from historical data and act on it by making decisions, sending feedback, or making tailored recommendations. A wide range of applications operates under this category of AI, such as chatbots, virtual agents (i.e., Siri, Alexa, Cortana), voice recognition agents, some processes within self-driving cars, and many more.

Tesla and Mitsubishi Electric are some of the many companies exploring Limited Memory technology for years. Typical AI systems (e.g., deep learning), are trained by a huge amount of data stored locally, creating a reference model that could potentially solve upcoming problems. Chatbots, virtual assistants, and image recognition applications use vast amounts of data, and their labels teach the system to name objects it recognises. When AI scans an image, it utilizes the training images as references to identify the subjects displayed in the picture. The accuracy in identifying and labelling the new images relies on the previous learning experience.

(c) Theory of Mind

Theory of mind applications can understand the environment and the individuals around it. It is a more sophisticated category of AI, requiring a comprehensive understanding of the individuals, the physical surrounding, and objects, and can alter feelings and behaviours. It senses people, their needs, emotions, beliefs, learned experiences, and thought processes. A theory of mind level AI can understand the surrounding environment, the objects, and entities and then interact with them. Although *artificial emotional intelligence* is an emerging industry, reaching the theory of mind level still requires development in other AI branches. AI machines will have to perceive humans as individuals whose minds can be influenced by multiple factors, essentially “understanding” humans. A real-world model of a theory of mind AI system is Kismet, a robot head developed by a researcher at MIT by the end of the 1990s [261, 260]. Kismet can mimic human emotions and recognise them. Both abilities are critical advancements in the theory of mind AI, although Kismet still has limitations on following gazes or conveying attention to humans.

Theory of Mind competency comprises both social and cognitive skills. It enables machines to think about their own status within an ecosystem, interact with peers, and sense mental states and emotions. Agents comprehend the context with other parties, what they may be thinking, and what could be different from their own thinking. As implied by its name, it is a theory, as no one would know the accuracy of thoughts on someone else’s mind.

(d) Self-aware

When robots and AI agents become capable of comprehending and replicating daily human practices, the next level is self-awareness. It extends the reach of the *theory of mind. Self-aware* requires agents to have self-guided thoughts and reactions and the ability to evoke human emotions in themselves and other parties. It requires an in-depth

Figure 22: AI Classification by technology

comprehension of the human mind and how it perceives the environment in real-time. However, there is no genuine theory yet establishing the principles and methods for self-aware AI. When robots are capable of sensing and fully understanding the environment, being conscious of what they do, and taking appropriate and timely initiatives, then self-aware AI will be realized. Machines will be able to learn from their own experience and be mindful of how they came to understand what they already know [275]. A thorough comprehension of the environment, including the agent itself and the effects on the environment, requires its self-awareness, which in turn emerges as a result of this understanding and the distinction that the agent can make between its own mind-body and its environment. Along those lines, [275] developed five potential issues: (i) agent perception and interaction with the environment; (ii) learning actions; (iii) agent interaction with other agents–specifically humans; (iv) decision-making; and (v) the cognitive architecture integrating these capacities.

AI *self-aware* technologies refer to the hypothetical future stage of AI development. It is a concept that AI will evolve to act like the human brain, capable of developing self-awareness. It is still speculative a timeline to implement self-awareness on machines. There have been several efforts to create models for synthetical consciousness, and the trend is expected to continue for many decades [276, 277]. AI *self-aware* will be able to understand, sense and induce emotions considering the surrounding environment, and also display emotions, demands, opinions, and potentially desires of its own [278].

AI classification can also focus on its capabilities towards helping to advance humanity and is subdivided into three groups: (f) Artificial Narrow Intelligence (ANI), (g) Artificial General Intelligence (AGI), and (e)Artificial Superintelligence (ASI).

(e) Artificial Narrow Intelligence (ANI)

Artificial narrow intelligence, *weak AI*, or *narrow AI* represents the most complex AI systems created to date. Chess-playing, medical diagnosis, self-driving vehicles, algebraic calculation, and mathematical theorem-proving are some applications in this class [279]. Existing bots serve as a classic example of narrow AI at work. A bot is a piece of software, an agent that can execute automated tasks that are generally simple and repetitive daily. Bots can reply to questions such as "Where should I choose for lunch?", "What is the weather going to be like today?", "How many new customers are expected next week?". It draws data from a larger dataset and delivers a tailored answer to the user. In parallel with AI classification by functionality, *narrow AI* incorporates the types of *reactive machines* and *limited memory*. Even complex AI system, such as machine learning and deep learning, falls under ANI.

Any knowledge gained from completing that task will not automatically be applied to other tasks. Although it can successfully mimic complex processes, e.g., language translation and image recognition, it has a narrow range of competencies. Although these machines may seem intelligent, they operate under limited constraints and limitations, which justifies categorising them under the *narrow* or *weak* type of AI. Narrow AI does not imitate human intellect - it only reproduces human behaviour given a narrow range of constraints, attributes, and contextual parameters.

(f) Artificial General Intelligence (AGI)

Artificial general intelligence (AGI) is the stage when an AI agent can perform any intellectual tasks like humans. While *narrow AI* can perform single and complex tasks exceptionally well, AGI extends the reach to mimicking human behaviour. It can likely learn, perceive, understand, and function similar to human beings. They can build up multiple competencies independently, form connections, and make generalisations across distinct domains. Although it remains in a hypothetical domain, AGU agents can replicate human multifunctional capabilities and significantly reduce the time needed for training. AGI agents focus on improving efficiency by performing cross-domain optimisation. AGI agents deal with "*the ability to achieve complex goals in complex environments using limited computational resources*" [280].

(g) Artificial Superintelligence (ASI)

ASI (hypothetical) agents are expected to possess intelligence beyond human capabilities. As larger and faster memory access is available, data processing and analysis happen faster, enhancing decision-making. Besides replicating the multi-faceted intelligence of human beings, ASI agents will be trained much faster. ASI supposes to make possible the existence of a 'superintelligent' AI agent.

The development of AGI and then ASI are expected to lead to a scenario referred to as the singularity, a theoretical point at which technological development becomes uncontrollable and irreversible, impacting significant changes to the planet and human civilisation [281, 282].

There are plenty of optimistic and pessimistic views around artificial intelligence (AI) today. Some optimists believe AI is a compulsory and natural evolution leading humans to newer experiences beyond the body of knowledge available today. Others predict that AI will end many things: jobs, warfare, and even the human race [283].

2.5.2 Deployment of AI on Energy Systems

AI is expected to contribute to the energy sector in the coming years significantly. It can help overcome the stochastic nature of renewable sources and improve methods for traditional solutions. Below are some functionalities that AI technologies can deliver towards supporting users and decision-makers to improve sustainability:

- Forecast energy supply, demand, and carbon footprint. Increased accuracy in short-term demand forecasting can significantly assist individuals in making educated decisions.
- Enabling full autonomy through intelligent power consumption, power storage, rationalisation, use category prioritisation and many more.
- Enhance mechanisms for power-sharing, bartering, or trading among neighbours.
- Enhance integration among the many subsystems in a decentralised power network.
- Forecast weather conditions.
- Balancing power supply versus load to enhance dispatch efficiency.
- Improve fault diagnosis and prevention.

- Predict Maintenance for infrastructure.
- Enable integration with electro-mobility vehicles.

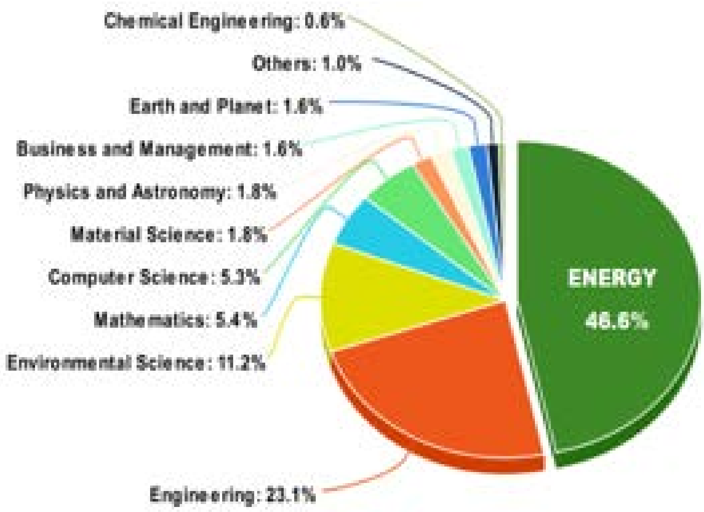


Figure 23: ML Applications distribution per segment

2.5.3 Deployment of Machine Learning in Energy Systems

Popular ML models in the energy sector include the "artificial-neural-network" (ANN), "Extreme-learning-machine" (ELM), "support-vector-machine" (SVM), "adaptive-neuro-fuzzy- inference-system" (ANFIS), deep learning, decision trees, advanced hybrid ML and ensemble models [284]. The stochastic nature of renewable power systems and the significant complexity of data make the ANN technique a good fit for power prediction [285]. Figure 23 shows the growth of research on energy systems and different subject areas that have used ML for the last two decades [286].

Most ML models in energy systems focus on predictive modelling of power supply, load demand, and demand analysis due to their accuracy, efficiency, and speed [287, 288]. ML models can also help improve understanding of energy system functionality and complexities with human interactions [289, 290, 291]. ML models on renewable energy systems have continuously evolved. There has been a significant number of academic papers presenting challenges and opportunities [292, 293, 294]. Nevertheless, most of these articles either survey applications of a specific ML model, e.g., ANNs or deal with a single power domain, e.g., solar power prediction. As a result, the innovations of ML models in various energy systems are still progressing with enough room for further research and new approaches.

2.5.4 Deep Learning in Energy Systems

A "*segment-level change detection to identify human activities change with very low computational complexity*" has been proposed by [295], where a "*fully convolutional network (FCN) with a high* *recognition rate is used to classify the activity only when activity change occurs*". The authors evaluated the truthfulness and power consumption of the method being suggested with the method built for convolutional neural network (CNN). In this case, it used a public dataset on distinct embedded systems. The experimental outcomes demonstrated that even though the detection rate of the suggested FCN model is comparable to the CNN model - FCC consumes only 16.6% of the energy when compared to the CNN-based method, and only needs 10% of the network limits of the CNN type.

Various categories of Deep Learning (DL) algorithms applied to solar and wind power systems have been discussed by [296]. The authors also evaluated the algorithm performance through a new taxonomy. Common challenges of DL techniques involve accuracy, robustness, precision values, and generalisation, which leads to different results. In the case of large-scale datasets, the computational cost of DL algorithms is significantly higher when compared to other Computer Intelligence (CI) methods. Nevertheless, deploying hybrid DL techniques with other optimisation techniques to enhance optimisation is highly stimulated. In general, hybrid networks have higher performance when compared to a single network, their hybrid nature takes advantage of multiple methods to deliver predictive tasks more accurately.

2.5.5 Reinforcement Learning in Energy Systems

Reducing energy deployment and operational cost, consumption, optimisation, and leveraging availability and comfort is a constant challenge for producers and consumers. [297] presented RL techniques on a household to evaluate and create a baseline to train the model, before sire implementation on site. The RL algorithm is capable of learning consumption patterns and generates an optimised schedule for heating, ventilator, and air conditioning, within an acceptable time interval to fulfil user needs. Initial findings revealed a 17% decrease in power cost and a 15% reduction in energy utilization using our RL algorithms.

[298] proposed an off-policy model-free reinforcement learning approach aiming to generate energy feasible paths for EVs from source to target. The authors suggested a mathematical for online applications. The findings demonstrated the algorithm's ability to make refreshing decisions and produce the most feasible energy paths. [299] presented a thorough review of several RL techniques and how they could be applied in the decision-making process and control of energy. RL is often applied in voltage control, frequency rate management, power control and critical issues such as safety, robustness, and scalability.

2.6 SUSTAINABILITY

The environmental impact has been a concern to humans since the Ancient Age. Plato (5th century BC) and Pliny the Elder (1st century AD), discussed the different types of environmental degradation resulting from human activities such as farming, logging and mining [300]. Tertullian was impressively concerned with the sustainability aspects of the planet resulting from over-population around the 2nd century AD: [*"If you look at the world as a whole, you cannot doubt that it has grown progressively more cultivated and populated. Every territory is now accessible, every territory explored, every territory opened to commerce... everywhere people, everywhere organised communities, everywhere human life. Most convincing as evidence of populousness,* ***we*** *men have actually become a burden to the Earth, the fruits of nature hardly suffice to sustain us, there is a general pressure of scarcity giving rise to complaints, since the Earth can no longer support us*" (De anima xxx)] [301].

The narrative of progress has complex historical roots and conflicts with the notion of sustainability. Progress can be perceived as one of the most influential myths of modernity – precisely as the central religious myth of our time [302]. In the Middle Ages, the Christian conception of progress blossomed – initially as a chance for improving this world in preparation for the next life and later upgraded to an opportunity to reach a more comfortable and desirable living state. This newer class of beliefs enabled colourful perspectives to humankind, bringing several consequences to the planet [303]. The "Great Idea of Progress", the "belief in progress", can be renamed the "Mith of Progress" [301], which implies that the notion of illimited and unstoppable progress is deeply rooted in the Christian theology of history. Environmental depletion is rooted in the "Mith of Progress", disseminated over into the formal and informal education systems since *development* and *consumerism* are mere byproducts of *progress*.

Environmental sustainability is an abstract concept directly linked to economics and socialism. It is founded on the premise of maintaining rates of renewable sources, restraining greenhouse gas emissions, and avoiding the depletion of non-renewable supplies. Economic sustainability refers to the capacity of supporting a defined level of economic production for an indefinite period. For last, social sustainability refers to the ability of a local community to function indefinitely at a defined level of social well-being [304].

The term "sustainable" has been used since the 17th century, meaning bearable, defensible, and secure) – more recently, it has been linked to the environment, economics, society or even a development process. Energy sustainability is about providing reliable, and affordable energy in conformity with social and environmental requirements [305]. Around 1950, Leopold affirmed that "*sustainable development is the organising principle for sustaining finite resources necessary to provide for the needs of future generations of life on the planet"* [306]. It is a concept that foresees an attractive future state for the society in which living conditions and resource use continue to meet the society's needs without destabilizing the "*integrity, stability and beauty*" of natural biotic systems. This initial definition emphasizes a prevailing principle of sustainable development, the need to leverage the use and protection of resources.

The World Commission on Environment and Development (Brundtland Commission) defined sustainable development as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." This description worked as a basis during the United Nation's Earth's Summit meeting (Rio, UN, 1992), the World Summit on Sustainable Development and the UN Conference on Sustainable Development [307].

There are so many definitions of sustainability that serve as an alert to remind of its abstract and contextual nature, e.g., "*global and local, temporal and spatial, measurable and non-measurable, and clear and ambiguous"* [308]. Sustainability can be contextualised in so many ways, making it difficult to assert the core meaning. Depending on the subject domain, sustainability may refer to "*climate, biodiversity, agriculture, fishery, forestry, energy and resources, water, economic development, health, and lifestyle"* – and [309] proposed a framework for sustainability science including "*goal settings, indicator settings, indicator measurements, causal chain analysis, forecasting, backcasting, and problem–solution chain analysis"*.

Quantifying sustainability is challenging and debatable, given the high level of subjectivity, countless variables, legal and technical constraints, and time-space considerations. Vagueness and the absence of scientific proof are normal. Sustainability has been deeply contaminated by marketing and propaganda, making it difficult to distinguish what is disinformation and what are facts. It has become a line of business, an umbrella with many sub-products (e.g., green certificates, eco-labels) - in many cases, overexploited by organisations willing to present an environmentally responsible public image.

Greenwashing is a misleading practice widely explored by all types and sizes of organisations – and individuals. It is an offshoot of poor legislation and the educational system mixed with appalling business manners. Greenwash happens in different layers, firm-level execution, firm-level claim, product-level execution, and product-level claim [310]. Stakeholders may engage a particular service provider to carry a package of tasks from one of the many standards – and claim "evidence" to be environmentally spotless. It is far more deceiving and harmful to the planet than society can comprehend. It undermines all efforts to mitigate climate change, enabling the problem to worsen [311].

Nation-states have territorial targets to meet. The IPCC agenda for Sustainable Development Goals (SDG) allows flexibility and provides tools for mitigation, leaving room for manipulation and ambiguous interpretations. [312] presented an enabling process for countries to describe national targets with associated standards for countries. The method builds upon the precedent set in other countries, particularly on a process created for establishing resource quality objectives in South Africa.

2.7 SUMMARY OF THE RELEVANT RESEARCH PAPERS

Table 01 shows relevant papers that contributed to finding the research gap in this research.

Table 1: Summary of relevant research concerning blockchain, AI, IoT energy transaction

Ref.	Literature Review Papers: BEST OF THE BEST (CA2)	Microgrids	Nanogrids	Picogrids	Femtogrids	Autonomous Microg.	P2P Energy Trading	Game theory	A.I. /ML. /DL /	Blockchain	Game Theory	Forecasting Algor.
1	A literature review of Microgrids A functional layer based classification.2016+++.pdf	√										
2	Microgrids Literature Review through a layers structure.2019.pdf	√										
3	A review of nanogrid topologies and technologies.2016.pdf		√									
4	PicoGrid Smart Home Energy Management System.2018.pdf			√								
5	DC picogrids_ A case for local energy storage for uninterrupted power to DC appliances.2013			√								
6	A review of forecasting algorithms and energy management..2018pdf.pdf	√										√
7	Day-Ahead prediction of microg elect demand using a hybrid artificial intellig model.2019.pdf	√										√
8	Very short-term wind power density forecasting through artificial neural networks for microgrid control.2018.pdf	√										√
9	Time series prediction using artificial wavelet neural network and multi-resolution analysis ...wind speed data.2016.pdf	√							√			√
10	Distributed double auction for peer to peer energy trade using blockchains.2019.pdf	√					√			√	√	
11	Incentivizing Energy Trading for Interconnected Microgrids.2018.pdf	√					√	√			√	
12	Peer-to-peer energy trading models.2018+++ .pdf	√					√					
13	An integrated blockchain-based en mgmt platf with bilateral trading for microg communities2020.pdf	√								√		
14	Optimization and integration of hybrid renewable energy hydrogen fuel cell energy systems – A critical review.2017.pdf	√										
15	An optimal P2P energy trading model for smart homes in the smart grid.2017.pdf	√					√					
16	Energy Crowdsourcing and Peer-to-Peer Energy Trading in Blockchain-Enabled Smart Grids.2019.pdf	√					√			√		
17	Peer to Peer Energy Trade Among Microgrids Using Blockchain Based Distributed Coalition Formation Methods.2018	√					√			√		
18	Distributed double auction for peer to peer energy trade using blockchains.2018.pdf	√					√			√		
19	An optimal P2P energy trading model for smart homes in the smart grid.2017.pdf						√					
20	A Motivational Game-Theoretic Approach for P2P En Trading.2019	√					√				√	
21	Synchronization Games in P2P Energy Trading.2018.pdf	√					√				√	
22	Machine Learning and Game Theory in Microgrids A Survey of applications, benefits...2020.pdf	√							√		√	
23	Reinforcement Learning in Energy Trading Game among Smart Microgrids.2016.pdf	√							√		√	
24	Energy trading game for microgrids using reinforcement learning.2017book++.pdf	√							√		√	
25	Intelligent Multi-Microgrid Energy Mgmt Based on Deep Neural Net and Model-Free Reinforcement Learning.2020.pdf	√							√			
26	(Deep) Reinforcement learning for electric power system control and related problems...review.2020s.pdf	√							√			
27	Intelligent Multi-Microgrid En Mgmt Based on Deep Neural Network and Model-Free Reinforc Learning.2020pdf.pdf	√							√			
28	State-of-the-Art Artificial Intelligence Techniques for Distributed Smart Grids_2020	√							√			
29	Transformation of microgrid to virtual power.2018++.pdf	√										
30	Microgrid supervisory controllers and energy manag.2016.pdf	√					√					

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Ref.	Literature Review Papers: BEST OF THE BEST (CA2)	Microgrids	Nanogrids	Picogrids	Femtogrids	Autonomous Microg.	P2P Energy Trading	Game theory	A.I. / ML / DL /	Blockchain	Game Theory	Forecasting Algor.
31	Optimization and integration of hybrid renew energy with hydrogen fuel cell energy systems – A critical review.2017.pdf	√										
32	Towards the next generaration of smart grids Semantic and holonic multi-agent manag of distrib en resour.2017.pdf	√							√		√	
33	Directed-Graph-Observer-Based Model-Free Cooperative Sliding Mode Control for DESS in DC Microgrid.2020.pdf	√							√		√	
34	Energy mgmt system for hybrid PV-wind-battery microgrid using convex programming,....2020.pdf	√										
35	An Energy Management System for Residential Autonomous DC Microgrid Using Optimized Fuzzy Logic Controller .2019.pdf	√				√			√			
36	Energy management system, generation and demand predictors.2017.pdf	√										√
37	Blockchains for decentralized optimization of energy resources in microgrid networks.2017.pdf	√								√		
38	Consortium_Blockchain-Based_Microgrid_Market_Tran.2019s	√								√		
39	Blockchains for decentralized optimization of energy resources in microgrid networks.2017	√								√		
40	Blockchain applications in microgrids_ An overview of current projects and concepts.2017	√								√		
41	A Blockchain-Based Energy Trading Platform for Smart Homes in a Microgrid.2018	√					√			√		
42	Towards resilient networked microgrids_ Blockchain-enabled peer-to-peer electricity trading mechanism.2017	√					√			√		
43	Evaluation model for multi-microgrid with autonomous DC energy exchange.2017.pdf	√				√	√					
44	G3 Powerline communication for controlling an Autonomous DC Microgrid.2019.pdf	√				√						
45	Energy Management System of Autonomous Low Voltage DC Microgrid....2018.pdf	√				√						
46	Distributed Tie-Line Power Flow Control of Autonomous DC Microgrid Clusters.2020.pdf	√				√						
47	PROTOTYPE_FOR_OFFGRID_SOLUTION_USING_SOLAR_AND_WIN.2020	√				√						
48	An Electrical Grid System for An Offgrid Isolated Place.2019pdf	√				√						
My thesis:	"It is possible to reduce emissions by deploying small and autonomous DC power plants, supported by Blockchain, AI an IoT.	√		√		√	√	√	√	√	√	√

2.8 KEY FINDINGS IN THE LITERATURE REVIEW

- Many publications have been identified in the *DC microgrids* domain, followed by a few in DC *nanogrids* and nothing in DC *picogrids* – none of them has an association with this research, which focuses on the autonomy, isolation from the AC grid aspects.

- The number of papers published in the AI/ML/DL (70,000 in 2021) field is higher than all the other papers combined in Blockchain, IoT, and Microgrids.

- The decision to adopt autonomous and decentralised DC small-scale power plants supported by Blockchain, IoT and AI models is the key differentiator from any other research.

- Finding a solution to the global emission problem requires a comprehensive understanding of many domains. The existing literature is segmented and does not tackle the emission problem as a whole – which does not help to solve the problem.

- The large majority of papers around technology have a business rather than scientific driver, e.g., optimisation, increasing performance, reaching masses faster – and do not present any environmental concerns.

- No study proposing an alternative solution for the power grid has been identified, making this research one of its kind in this field.

Table 2: Total citations in Scope, IEEE Explore and Springer

	IoT			Blockchain			ML /AI		
	Scope	IEEE	Springer	Scope	IEEE	Springer	Scope	IEEE	Springer
DC Microgrid	2	24	620	1	8	380	2	19	1900
DC Nanogrid	1	24	23	0	0	0	0	0	0
DC Picogrid	1	1	0	0	0	0	0	0	0

Chapter 3: Research Methodologies

This section presents the methods and actions to investigate the research questions and objectives discussed in section 1.4 (Chapter 1).

Objective 1: Identify sources, drivers, causes and potential root causes of global GHG emissions from the electricity industry.

- ❖ **Method deployed**: exploratory research and root cause analyses using the Ishikawa technique

Objective 2: Present an alternative model to the existing power utility system allowing consumers to interconnect through small-scale and autonomous DC power plants.

Objective 3: Present a model showing how Blockchain, AI and IoT can support households and decentralised power plants to reach sustainability.

Objective 4: Create a framework for the power utility system supporting a faster transition to sustainability.

- ❖ **Method deployed for objectives 2, 3 and 4**: Model-Based System Engineering (MBSE)

Objective 5: Present a comparative case study for *microgrids*, *nanogrids* and *picogrids* demonstrating that a Machine Learning model can make predictions with an accuracy of over 90% for one day ahead of power consumption.

- ❖ **Method deployed for objective 5**: Simulation experiment using ML predictive modelling tool (Data Science Studio -DSS) with data acquired from Dataport libraries for 73 houses in Texas, California and upstate New York (USA).

3.1 Exploratory Research to Identify the Root Causes for the Global GHG Emissions Problem

Exploratory study research is a methodology that investigates a problem that has not been clearly defined, or its boundaries are ambiguous, intertwined, or uncertain. The objective is better to understand all aspects of a problem or phenomenon so a solution can be drawn, a diagnosis, or an explanation for an occurrence. Unlike traditional research methods where deliverables are distinguished, measured, weighted, and classified, exploratory research is a dynamic process of searching, processing, learning, and reporting. New understandings may modify or invalidate previous conclusions and create new uncertainties. Objectives may change, expand or shrink. Assumptions made earlier may no longer hold on to later stages. If not adjusted, they may lead to constraints and time-wasting - a necessary and genuine part of the learning process. Uncertainties may be removed or replaced by new ones. The ultimate goal is to explore and expand knowledge boundaries. Exploratory research may be referred to as grounded theory or interpretive research when addressing questions like what, why and how.

In this study, exploratory research was conducted to find the emission sources, causes, drivers, and root causes – as a stepstone to gain skills to approach the global emission problem linked to electricity generation. In-depth online research followed by literature research has been conducted.

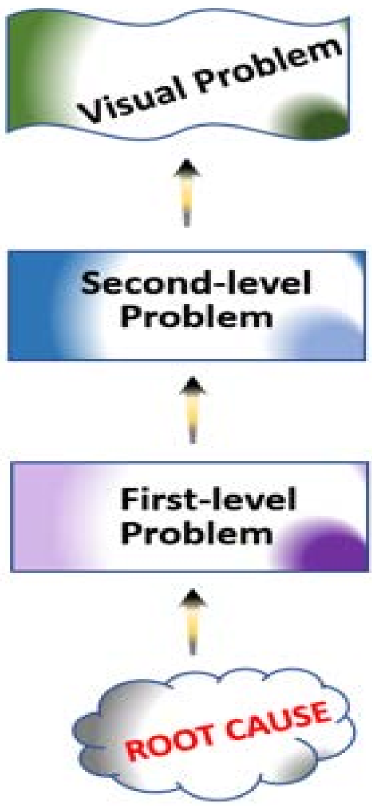


Figure 24: The concept of Root Cause Analysis (RCA)

Root cause analysis (RCA) is a systematic process for tracking the root causes of complex problems, which are not readily perceivable by the field engineers, scientists, or network operators. It can be related to anomaly detection, fault finding, or a long-term problem that affects a system or environment, however, that has never been adequately identified and analysed. RCA techniques can be applied to any engineering, industrial or medical domain. It helps to determine what, why and how it happened. Understanding the end-to-end process can help professionals decide on solutions to solve or reduce the likelihood of the same problem (or event) happening again.

According to the Department of Energy (DOE) in the USA, from its guideline for root cause analysis (DOE-NE-STD-1004), '*the basic reason for investigating and reporting the causes of occurrences is to enable the identification of corrective actions adequate to prevent recurrence and thereby protect the health and safety of the public, the workers and the environment"* [313].

Root causes can be physical, human, organisational, procedural, or even legal nature. It can be tangible, like a mechanical failure or abstract embedded in a vicious procedure, guideline, or regulation. A system, process, or policy that people rely on making decisions can be a hidden root cause that leads to an inadequate design.

RCA builds upon the idea that effective decision-makers require better processes to identify and prevent problems. It starts by describing the problem clearly, establishing the timeline for the occurrence, distinguishing the intermediated levels and establishing the causal factors and potential correlations until the root cause of the problem is reached (Figure 24.).

3.1.1 ROOT CAUSE ANALYSES TECHNIQUES

The most common techniques for root cause analyses are the (a) five whys, (b) fishbone diagram, also known as Ishikawa, (c) the regulatory forms, (d) the logic tree, (e) brainstorming, (f) flowcharting, and (g) affinity diagram [314].

Five whys is a simplistic, iterative and interrogative technique that explores the causal effect relationship underlying a problem. The key objective is to find the root cause of a problem or a defect continually reiterating the question "Why?". It is fast, light resource, inexpensive, and typically conducted by individuals (or teams). It may suit well when trying to avoid imprudent assumptions, however, it has limitations when dealing with complex and multi-domain problems. It may lead practitioners to stop at the first symptom and discourage more in-depth investigation of the root causes. The lack of knowledge of the researcher creates a limitation, so the investigator may be led to find what they already know, and disregard the unknown causes. Results are not often replicable – so, different users using the 5-Why technique may end up with very different causes for the same problem. In the end, the entire process may narrow down to a single root cause, whereas each question could lead to different root causes.

The simulated 5-Why technique is improbable to reach the depth required to find real the root causes [315].

The Ishikawa Diagram (or fishbone diagram, or cause-and-effect) technique encourages the identification of possible causes for a problem by following categorical branches to potential causes. The spine exemplifies the sequence of the most prominent events causing an undesirable outcome. The fish bones represent cause categories that can potentially contribute to the root problem. A fishbone diagram is a technique frequently associated with brain-storming. The group may decide to classify cause category, geographical location, usually highlighting the most apparent factor turns out to be minor, and the one that was thought to be minor is causing the issue. Often cause and effect diagram allows the team to think strategically about the root cause, leading to a sound and long-term solution [316].

The **affinity diagram** stimulates discussion about a question or problem, opening up possibilities for the development of a solution. It allows large numbers of causes resulting from brainstorming to be grouped for review and analysis based on their natural relationships. It may use a large volume of information, ideas, and user opinions from a wide variety of sources, e.g., brainstorms, databases, ethnographic research, user opinions, and more. The affinity diagram helps to manage ideas by recording each cause or card note, looking for causes that seem to be correlated, and classifying the causes until all cards have been used. It allows the creation of large clusters into subgroups for easier management and analysis. This technique requires strong involvement with the data, which has benefits beyond the tangible deliverables, and the best outcomes tend to be achieved when a cross-functional team completes the pursuit. The final output is the actual affinity diagram showing the most valuable insights to be included in the design process or to envisage a problem solution [317].

3.1.2 Root Cause Analyses For The Global Emissions Problem

All causal problems arise from their root causes. A thorough understanding of the underlying structure, the symptoms, the effects, the chronology of the events, actors, surrounding environment, triggers, conditionals, and every other aspect becomes relevant when finding a solution for an unsolved problem.

Global warming and climate change are well-established phenomena rooted in anthropogenic GHG emissions. In contrast, the global emissions dilemma is still largely miscomprehended by educators, influencers, decision-makers and the entire public. Finding the root causes of emissions is critical to mitigating the problem. So far, most attempts have been contributing to delaying and postponing the solution. GHG emissions levels (including CO_2, N_2O, real and measurable leave no margin for deniers [54, 55].

The root causes of emissions deal with the foundational problems, highly abstracted, such as constraints, conditions, or underlying rules forcing (or motivating) stakeholders to make decisions that favour only short-term goals. They are hardly noticeable by the public and may emerge spontaneously at times when individuals and organisations are only focusing on one aspect of a multi-level problem.

A series of techniques described in the previous subsection have been conducted to identify the root causes of global emissions, including mind map exercises, brainstorming, and the Five Whys method. The output is synthesised in the Ishikawa Diagram (Figure 25). Here are the highlights for each of the seven root causes of global GHG emissions:

1. **Institutions:** Promotes the lowest prices, and to lower production costs, producers deploy minimum transformation methods, combustion of fossil fuel without emissions' mitigation; Make use of lobbying, influencing power, protects institutions short term interest, disregard environmental effects, leading to more emissions;
2. **Education**: Primary school fails to raise students' awareness about the environment and prepares them to become active consumers; higher education has become a testbed for startups. The higher the HDI of a nation, the higher the emissions;
3. **Technology:** Multiplies productivity, can lead to negative behaviour, facilitates the acquisition process, and stimulates more acquisitions – which leads to more emissions;
4. **Legislation**: absence of law and regulation for global commons; nation-state legislation protects producers, consumers, and intermediaries; it stimulates higher production and fails to protect the environment; state sovereignty imposes extra difficulties to combat global emissions;
5. **Government national goals**: promotes the continuation of the emission problem. It solves a short-term local problem while contributing to extending and intensifying the long-term global issue. National strategies aim to secure (or expand) the existing benefits for the community. It encourages increasing in exports and productivity, leading to more GHG emissions.

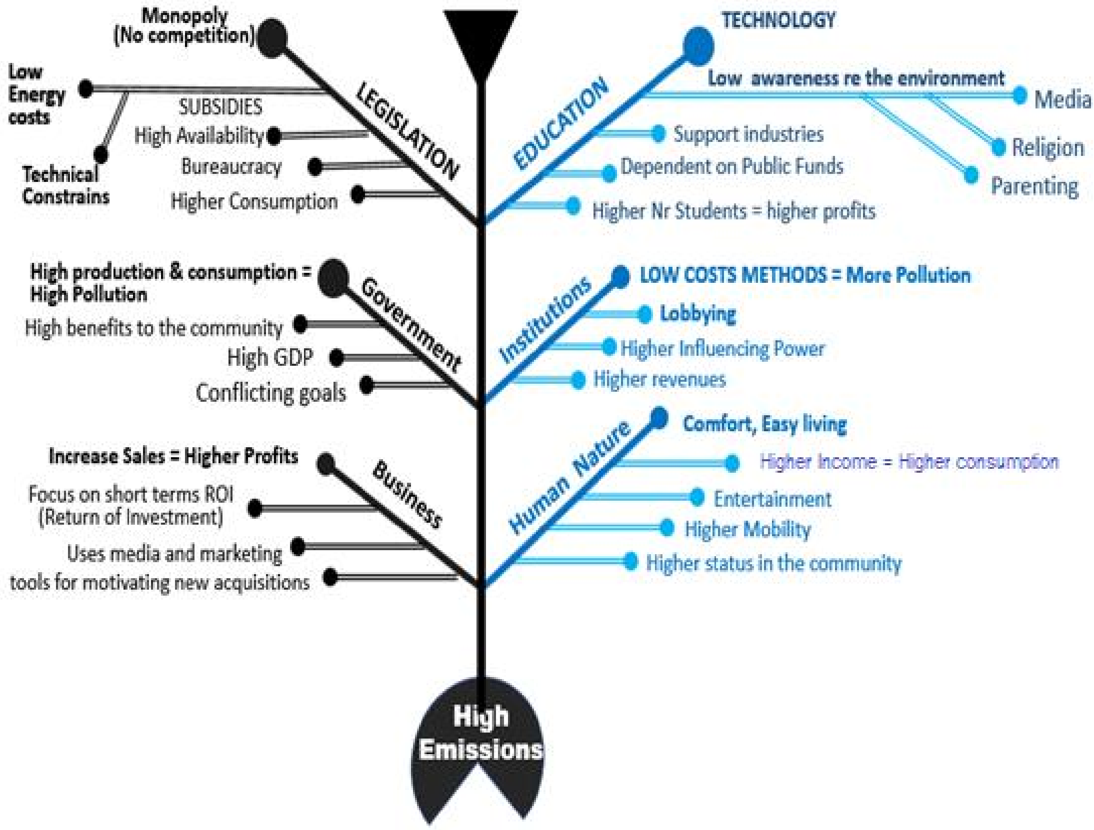


Figure 25: Ishikawa Diagram – Root Cause Analyses for emissions in the Electricity Industry

6. **Human Nature:** The higher the income, the higher the tendency for consumption, and consequently the higher the emissions per capita. Humans tend to value short-term benefits, comfort, and mobility instead of long-term benefits.

7. **Business:** Focuses on short-term results, stimulates exports, forces internal and external competition, increases networking, and the proliferation of transnational corporations, leading to more emissions.

3.2 MODEL-BASED SYSTEM ENGINEERING (MBSE)

System engineering (SE) emerged as a requirement out of the increased complexity in communications, instrumentation, computation, and control systems. The term was possibly first used by Bell Labs in the USA around the 1950s [318]. According to [319], SE can be defined as a "*multi-disciplined application of analytical, mathematical, and scientific principles for formulating, selecting, developing, and maturing an optimal solution from a set of viable candidates that has acceptable risk, satisfies User operational need(s), and minimizes development and life cycle costs while balancing Stakeholder interests*".

The term *systems* refer to a collection of entities and their interrelations (or a combined set of interoperable components, modules, or objects) with specific and confined resources arranged in different permutations. At its core, systems engineering aims to realise the complex system, accounting for the entire life cycle. The scope of SE includes the following aspects:

- Analytical Problem-Solving and Solution Development — Example activities include collaboration with external and internal Users to identify, specify, and bound their operational needs and capabilities; oversight of multi-level design development and integration; assessment of System Integration and Test results for compliance to specification requirements; and conduct and review of Analysis of Alternatives (AoA).

- Multi-discipline Engineering —Example activities include collaboration with Engineers concerning the development and interpretation of requirements, design integrity, analyses and trade-offs, prototype development, and Modeling and Simulation (M&S).

- Technical PM —Example activities include planning, tailoring, orchestrating, and implementing the technical project, including baseline and risk management, conducting technical reviews, Specialty Engineering Integration, performing Verification and Validation (V&V) oversight, and preserving the technical integrity of the project.

SE integrates several domains into a consistent group effort establishing a coordinated development process aligned with methods of production, and operations up to end-of-life (EOL). SE considers all customers' business and technical needs to provide a quality product that meets the user's needs. System Engineering can utilize systems thinking principles to consolidate this body of knowledge, and individual outcomes can be defined as a combination of components that work together to perform a proper function collectively [320].

SE can be seen as an engineering perspective, a process, or a professional field. It accounts for customer needs and functionality requirements, distinguishing and documenting them during the development cycle. It uses a design model and a system validation while considering the complexities over the entire life cycle: planning, scheduling, execution, operations, service support, performance, training, test, and disposal [321].

The International Council on Systems Engineering (INCOSE) defines System Engineering as *"a transdisciplinary and integrative approach to enable the successful realisation, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods* [322].

Several interpretations of SE can be employed to build complex systems and large-scale systems, such as the waterfall development model, V-Model, spiral development model, evolutionary development model, incremental development model, and Agile development model [323]. The most popular graphical representation of a system development life-cycle is the V-model, a top-down approach followed by a bottom-up methodology to the build, integration, and testing activities. That may also include validation of the as-built system against specifications. The V-model was conceived around the 1980s, and a few variants emerged across different industries. The V-model encapsulates the main steps in conjunction with the corresponding deliverables within the system validation framework or development project life cycle. It defines the sequence of activities to be executed and the expected results during the development life cycle. According to [321], Model-based systems engineering (MBSE) is a "*structured approach for modelling systems requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases*".

Conversely, document-centric engineering places the models at the system design centre. Unlike the tradition of "engineering with models", MBSE is a "*holistic systems engineering approach centred on the evolving system model, which serves as the baseline for the entire system*", as stated by [324]. The increased adoption of digital-modelling environments in recent years has led to an increase in the implementation of MBSE. For instance, in 2020, NASA observed this trend by asserting that "*MBSE has been increasingly embraced by both industry and government as a means to keep track of system complexity*" [325].

Systems development life cycle (SDLC) is a framework encompassing the overall aspects, end-to-end methods and procedures, for engineering software, systems, or information

Table 3: MBSE compared to Documented Based characteristics

	Document Based	MBSE Based
Information	- Mostly Text - Add Hoc Diagrams - Loosely coupled, repeated in multiple documents	- Visual and Textual - Constructs Defined once and re-used - Shared across Domains - Consistent notation in diagrams - Defined relationships
Information Views	- By Document	- Provides Viewpoints - Filters By Domain, Problem Space, etc.
Measuring Change Impact	- Spans across Multiple Documents - Often Text Reqts. Are isolated from Structure and Behavior	- Relationships define traceability paths - Natural part of the modeling process - Programmatically Automated
Measuring Integrity - Completeness, Quality & Accuracy	- By manual inspection	- Programmatically Automated - Animation of Spec

systems development. A “*system*” can be any IT constituent – a piece of hardware, software, or a combination. Every component of the system goes through the initial planning, execution, testing and disposal- as part of the development life cycle. Some methodologies provide a framework to guide the developer through the process and expedite results, moving the physical or software-based systems through phases. SDLC is comparable to a project life cycle, a phased project model that defines a large-scale systems project's organisational, personnel, policy, and budgeting constraints. The term “project” implies a beginning and an end to establishing a set of goals within a timeline, and budget, within clear and verifiable criteria.

The SDLC framework provides clear guidance and defined phases of work for all the components, planning, designing, testing, deploying, and maintaining the information system (IS). When relating to software package software, a clear distinction should be made between a software product and an IS. An information system consists of several software products or modules which are linked to each SDLC stage [326].

The V-model is a form of SDLC model where processes are executed sequentially in the verification and validation model (V-shape). The V-Model has individual deliverables and includes a review methodology. When sufficient data, resources, and technical expertise are available, the V-Model becomes suitable. Developers must have clear goals to meet the requirements of the deliverables within a set timeline, lowering the risks of time-wasting and resources.

SDLC model employs checks and balances to guarantee that all software is tested before being installed, industrialised and commercialised. SDLCs have well-organized documents for project goals and procedures, teams are flexible, and members can be replaced, causing a minor impact on the development. SDLC models enable components to iterate and improve upon themselves. Stages can be characterised in different ways and typically include (i) preliminary analysis and requirement definitions, (ii) system design (planning), (i) development, (iv) integration and testing, (v) acceptance, (vi) documentation, (vii) evaluation, (viii) disposal. The phases of an SDLC implementation provide natural guidance to streamline the system implementation, from the project's scope, providing an immediate high-level vision of a proposed system, from conception to retirement.

SDLC waterfall is a classic implementation model, the first of its kind, widely deployed in a linear-sequential fashion following a logical progression. A chronological sequence in which the output of one serves as the input for the next phase (Figure 26). Key waterfall principles include sequential structure, phases, requirements, design, implementation, verification, and maintenance.

System design refers to constructing, building elements of a system, the architecture, modules and components, dimensioning and defining the different interfaces for each component, and the type of data, format and structure flowing through the system. System Analysis is the process that disaggregates a system into parts toward defining how well those components perform to achieve the required goal.

The main elements of a system include (i) the conceptual model or architecture, which provides an overview, usually in a graphical format, of the entire structure, the modules, main characteristics, behaviours, and interfaces; (ii) the modules performing specific functionalities, handling specific tasks; (iii) the components which execute related functions for a module; and (iv) the internal and external interfaces (e.g., between components, modules, user interface, the Internet, external systems), and (v) the data.

This section describes in more detail each phase of the SDLC framework, the modules, and systems components, objectives and key deliverables. Then, in chapter 5, this research presents a design model for the electrical power systems (the ADCx model), a model for integrating Blockchain, AI and IoT (BAIoT model) to maximise opportunities for small-scale and decentralised power plants, and a framework that provides the guidelines on how to overcome major roadblocks to reach sustainability.

Figure 26: Typical SDLC framework (6 phases)

3.1.1 ADCX SYSTEMS DESIGN

The ADCx concept includes the power generation system (PGS), the energy storage system (ESS), and the load management system (LMS) (Figure 27). The GeSLOCx is the central unit for the ADCx model, an engine that controls and interacts with all the subsystems and external unities.

3.1.2 GeSLOC Concept

Figure 27 shows a graphical representation of the GeSLOC engine in a *picogrid* environment. The sequence of events is indicated, followed by a brief description of the functionalities of each sub-component (Figure 28). Sensors can detect the action when an appliance is switched on and transmit the data to appropriate agents. The information is registered in a local database and, in the meantime, triggers a supervising task by another agent. Load consumption and power availability are checked, and decisions are made on whether the power supply should come from the main supply or batteries (storage system). Depending on the status, users will be reached to make adjustments or take corrective actions to meet network demand.

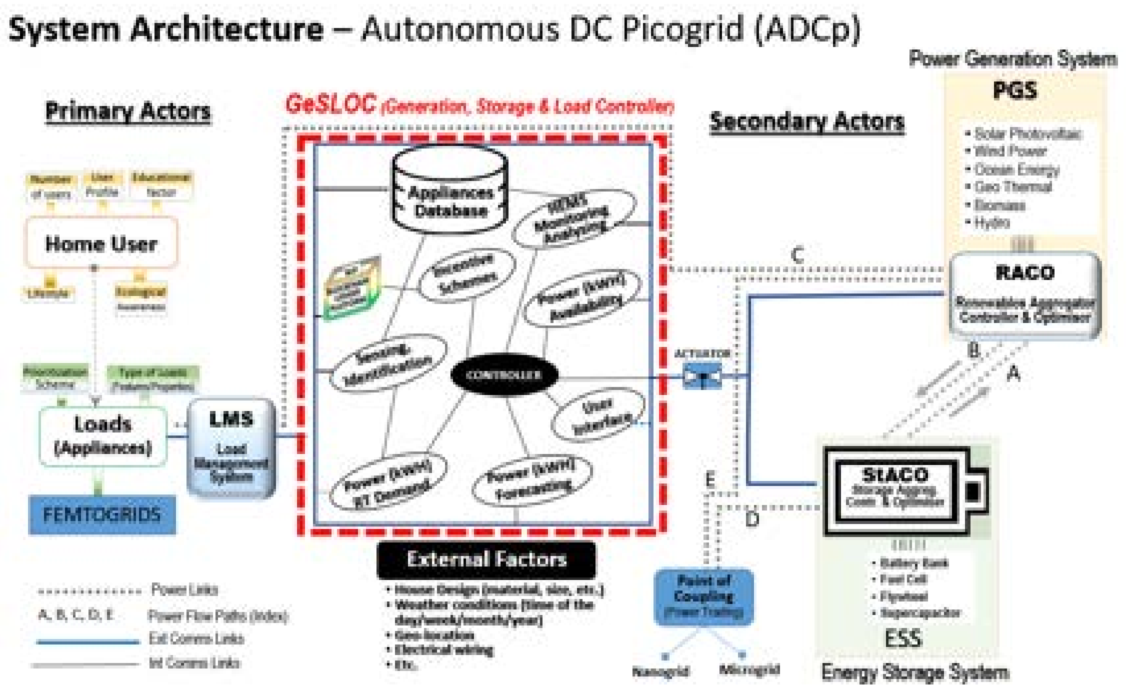
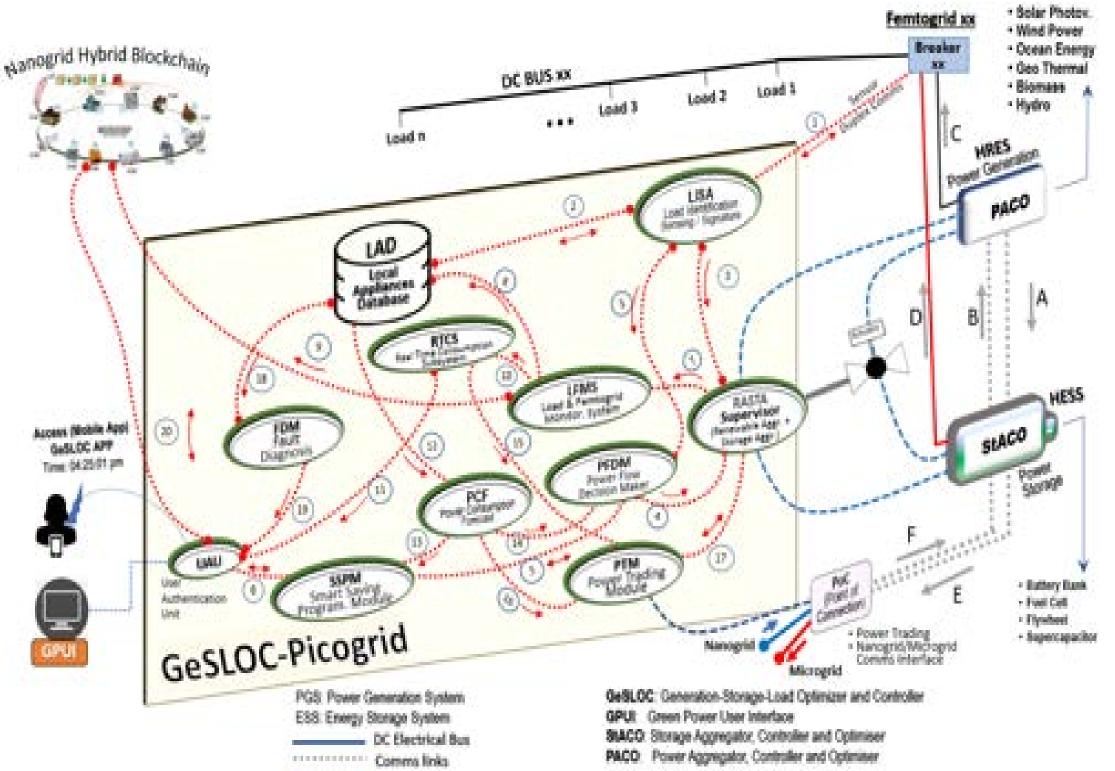


Figure 27: System Design for the ADCp with main modules and interfaces

Figure 28: GeSLOC System Operations in a picogrid



(1), (2)	**LISA**	The *Load Identification-Sensing & Authentication* module measures the current & voltage, disaggregates the signal, and identifies the load through a digital signature scheme previously uploaded to the LAD database. It gets electrical inputs from the load and performs some checking and handshaking activities with the LAD database. It then determines what appliance is in action. Next, LISA sends a signal to RASTA and PFDM at the same time.
(3)	**RASTA**	The Renewable Aggregator & Storage Aggregator (RASTA) unit continuously supervises the RACO and STACO units and sends a command to the Actuator. It keeps track of the amount of renewable power being produced and stored. It gets input from LISA and PDFM on how to proceed and balance the load, supply, and storage. E.g., it may send power directly from the Solar system to a Fridge, etc. RASTA has three levels of decision-making. The default mode is when power generated is directly sent to the load. Otherwise, power could be stored or exported to other neighbours via PoC (Point of Connection). RASTA may require inputs from PDFM or SSPM before making a decision.

(4)	**PFDM**	The module ***Power Flow Decision Maker*** is in charge of computation and analytics supporting the entire system. It receives real-time data from LISA and forecasting from PCF, conducts the analytics and guides RASTA and SSPM. This module houses the AI/ML agents that send data to RASTA forward to LFMS and Blockchain. It computes the network's power status and evaluates the best course of action, considering all the possibilities. The goal is to maximise opportunities and mitigate any potential risks.
(5), (6)	**SSPM**	The ***Smart Saving Program Module*** contains the level of priorities of appliances. It reflects the user's preferences on what appliance should have a higher priority under what scenario. Also, the SSPM contains algorithms that motivate and induces the user to take proactive actions toward energy savings. Under certain circumstances, SSPM may send an educational message to the user, ask for input, or even provide a suggestion for future action. SSPM gets input from the PCF unit
(7)	**LFMS**	**The *Load & Femtogrid Monitoring System*** is triggered by RASTA. It continually measures the power involved (current, voltage, time of use) for each appliance – after PDFM/RASTA decides on the path. LFMS continually sends info to LAD, RTCS and BLP (Blockchain Ledger platform
(8)	**LAD**	The ***Local Appliance Database*** contains the appliances IDs, electrical Specs, and names. The user admin provides the details for each appliance and to what Femtogrid it is connected. Also, LAD keeps the historical consumption details (amount of power, timing) for each appliance and per *picogrid*. These inputs come from the LFMS unit. LAD supplies info to the RTCS module.
(9)	**GBPP**	***Green Blockchain Picogrid Platform*** is a second-level database built on digital ledger technology. BLP lists all energy flow events within the *picogrid* environment. It gets the info from LFMS and registers the events in chronological order. Hashing function, digital signature and cryptography enable a high degree of data integrity and immutability of the sequence of events. It creates a high level of trust between unknown users that otherwise would have to be provided by a third party.

(10) **(11)**	**RTCS**	The ***Real-Time Consumption Subsystem*** provides precise consumption details in a graphical format for all loads, Femtogrids and the entire *picogrid*. It gathers information from LFMS and summarises and produces graphics for the user.
(12) **(13)** **(14)**	**PCF**	The ***Power Consumption Forecast*** module uses historical data from LAD to make predictions on future demands. It uses external input tools (weather forecasting), number of users, consumer profiles, and tailored prediction algorithms. PCF supplies inputs to PFDM and SSPM units for power flow decision-making and smart savings.
(15) **(16)** **(17)**	**PTM**	The ***Power Trade Module*** receives information from RTCS (Real-Time Consumption Subsystem) and compares it with PCF (Power Consumption Forecast). Also, it Checks with RASTA if there is a shortage or oversupply of energy. Depending on the outcome, it sends a message to the Actuator via RASTA to send power to the Point of Connection for Nano/Microgrids.
(18)	**FDS**	The ***Fault Diagnosis System*** checks the actual amount of power that is being consumed by a given load over a period of time and compares it with its specs stored in the LAD. If the consumption does not fall under a limited threshold, it implies there may be some fault somewhere. Then, it sends alerts to the user to take corrective actions.
(20)	**UAU**	The ***User Authentication Unit*** allows mobile phones, desktops, and tablets to access the user's credentials and permission level. UAU must authenticate all requests from the users.

3.2 COMPARATIVE CASE STUDY

Case studies research strategy is commonly used in systems engineering, system development, software engineering, and information systems. A case study applies to situations when little is known about a field and often tends to be descriptive, but not always. Among several definitions, [327] defines a case study as a '*strategy for doing research that involves an empirical investigation of a particular contemporary phenomenon within its context using multiple sources of evidence"*. Another well-known definition for a case study: *"an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and its context are not evident",* as put by [328]; Or, in a more elaborated form: *"a case study examines a phenomenon in its natural* *setting, employing multiple methods of data collection to gather information from one or a few entities (people, groups, or organisation). The boundaries of the phenomenon are not evident at the outset of the research, and no experimental control or manipulation is used* [329].

In software engineering, a case study can be described as *"an empirical enquiry that draws on multiple sources of evidence to investigate one instance (or a small number of instances) of a contemporary software engineering phenomenon within its real-life context, especially when the boundary between phenomenon and context cannot be specified"* [330].

A case study is often used in combination with *field* and *observational studies*, aiming at a specific goal, or standpoint, within the research methodology. When involving study changes, they are often referred to as *action research*. This variety of terms may cause misunderstandings when aggregating various empirical analyses and reusing research methodology guidelines from other research fields [330].

A survey is a "*collection of standardised information from a specific population, or some sample from one, usually, but not necessarily using a questionnaire or interview*" [327]. Surveys offer an outline of a research field rather than an in-depth study.

A controlled experiment "*measures the effects of manipulating one variable on another variable – and subjects are assigned to treatments randomly*" [331, 327]. The impact of one particular variable is studied in multiple trials. *Quasi-experiments* are like controlled experiments, however, "*subjects are not randomly assigned to treatments"* [332]. When performed in an environment, quasi-experiments can have distinct characteristics across case studies [330].

Action research is an interactional investigation method that leverages problem-solving activities in a cooperative approach. It builds upon data-driven collaborative research to find the underlying triggers for future predictions. Action research can "*influence or change some aspect of whatever is the focus of the research*" [327]. Therefore, action research is directly associated with case studies. Whereas case studies tend to be observational, action research is more concentrated on the 'changing' aspects.

Depending on the context, action research may involve a series of iterations, with each step of the case series changing exactly one variable from the research design examined in the previous example. In such cases, action research may be considered an *iterative case study*. This is typical in applications for software process improvement and technology transfer studies [331].

Comparative case studies build upon the analyses of similarities, syntheses of differences, and patterns across two or more cases with a common focus or goal [333]. It differs from a traditional case study by allowing for simultaneous comparisons, resulting in superior, multi-dimensional generalisation knowledge across several cases. *Comparative case studies* thoroughly examine the context and features of multiple instances of specific phenomena. *Comparative case studies* strive for macro analyses, from single case studies, aiming to find contrasts, similarities, or patterns across several cases. The outputs may contribute to the development or the confirmation of theory [334]. [335] argues that comparative case studies are heuristic approaches attending to macro, meso, and micro dimensions of case-based research. It can help direct the best approach for a particular research problem – or serve as a directive for larger programs.

The comparative case study has been selected for this research to identify the best interval for data collection of consumption data across *microgrids*, *nanogrids* and *picogrids*. Six cases were studied, sharing the same configurations, with a common focus on producing knowledge and establishing similarities, patterns, synthesis, and analyses between the cases. It enabled easier conclusions and more sound generalisations on how consumption profiles can vary depending on the amount of data supplied during the same period. For instance, what would be the difference if data is sampled each 1 second, 1 minute or 15-minutes in forecasting power supply and load consumption?

3.3 METHODS FOR DATA COLLECTION

There are three main methods involved in this research, implying there are three methods for collecting data. For the root cause analyses aiming to identify emission sources, drivers and root causes (objective 1), the data was collected from academic articles, peer-reviewed journals, conference proceedings, media, informal sources, and brainstorming. Once the direct and indirect emission sources (and causes) were identified, it was possible to gain more clarity on the root causes of emissions. Moreover, from the root causes, it was then possible to draw two conceptual models (ADCx and BAIoT) and a framework (BAIoTAG) for overcoming existing barriers and enabling a transition to sustainability.

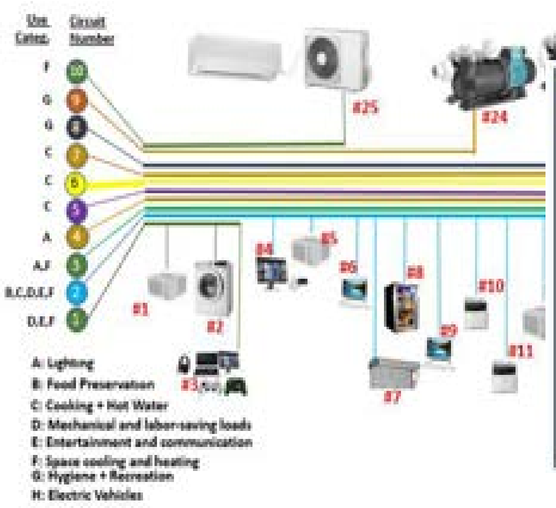
For the ADCx, BAIoT models and the BAIoTAG framework, objectives 2, 3 and 4, there was no requirement for data collection since they are conceptual design models in the attempt to solve the global emissions for the electricity industry. As GHG emissions rates keep rising almost steadily [39, 36, 336], and the absence of alternative solutions, this research undertook this challenge by proposing a solution to the problem. The models are unique in addressing all the root causes of emissions. A synthetic dataset has been created to prove the concept of Blockchain, AI, and IoT under the BAIoT system and the integration with the power subsystems.

For the comparative case study (objective 5), the first challenge was to decide whether the research should rely on locally acquired from a single house versus using more robust external data. Both options were considered and tested. While installing sensors and collecting local data via energy management systems was important to prove the IoT automation aspects, it turned out to be less beneficial to conduct ML analyses, where a massive amount of data is mandatory. Consolidated data was acquired from Dataport libraries in the USA [337] for 73 houses in Texas, California and upstate New York. Pecan Street Inc. research group has been collecting power consumption data for over six years, including 1,115 homes and businesses, making it available for registered customers, including many universities worldwide. Two compliance requirements were fulfilled: (a) the registration as an academic student and (b) the user license agreement between Pecan Street Inc and the University of Technology of Sydney requirements [338].

3.3.1 DATA ACQUISITION FOR BLOCKCHAIN-IOT EXPERIMENT

Current sensors have been installed in a house and connected to a Smappee device [240], with processing and routing capabilities. Then, a synthetic data generator was created to simulate power consumption events randomly published at the Heroku cloud platform. Usage categories then classified data, and the results were published on a Blockchain platform for demonstration purposes. The data collection undergoes two processes, as demonstrated in the following sections.

3.3.1.1 A single house using Smappee gateway, Node-RED and Current Sensors



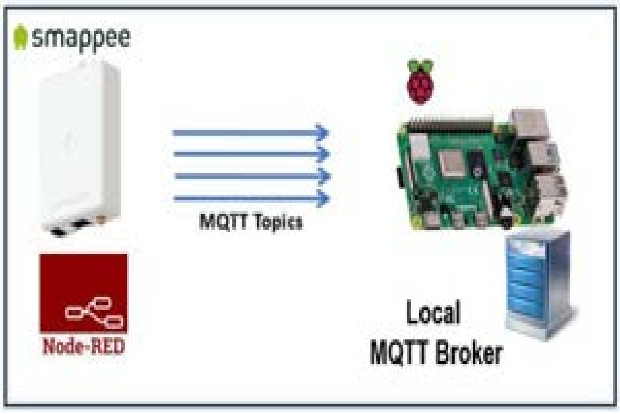


Figure 31: Smappee with Node-RED engine sending data to a local MQTT Broker

Figure 29: Existing Power Layout Diagram - hous

Figure 29 shows ten electrical circuits from a household feeding 25 appliances. Use categories grouped appliances, and eight current sensors were installed at the switchboard.

Each sensor measures voltage, current and active power at regular intervals (e.g., 1-minute, 10-minute) for a group of appliances, referred to as femtogrids. Individual sensors are connected to a switching hub installed in the garage, which is also connected to the Smappee gateway.

The Smappee device (gateway) receives the data from the sensors and publishes it via the MQTT Broker (Figure 30). It can be sent externally via an external MQTT broker, e.g., installed in Raspberry Pi, or it can use the built-in functionality in the Smappee gateway. The

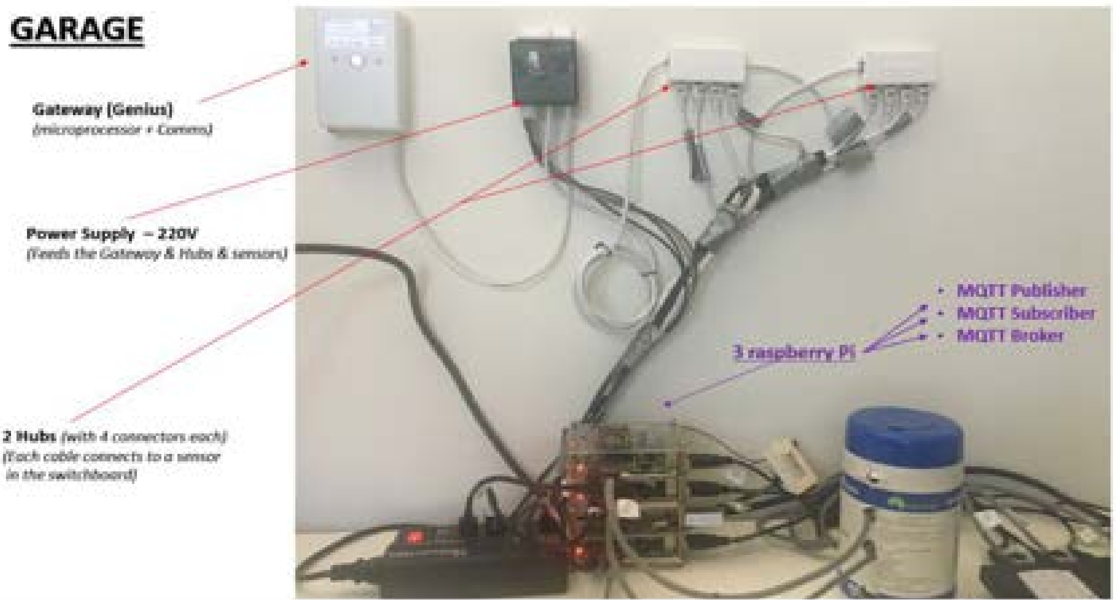


Figure 30: Smappee gateway with 2 Hubs and power supply

gateway is equipped with an MQTT broker that continuously pushes the MQTT data (topics), so it can be collected and saved locally or in the Smappee cloud. In this case, the MQTT subscriber functionality is installed locally in a Raspberry Pi, which stores the data locally.

The gateway has a Node-RED built-in engine, so data is automatically published at the MQTT broker. The broker publishes the data in different message topics, which contain the consumption values in real-time or aggregated data for a given period (e.g., 1 minute, 5 minutes).

The message topics are communication channels that enable the subscribers and publishers to communicate. The message topic allows the system to distinguish what type of information flow in that channel, e.g., voltage, current, or active power. Only devices subscribed to a particular channel can access the MQTT broker on that same channel (Figure 31).

Figure 32 shows a snapshot of the data published by the MQTT broker in real-time with consumption data for each of the 08 current sensors. This data is accessed locally on IP 192.168.1.106/smappee.

Figure 32: Snapshots from Smappee cloud referring to 08 current sensors data

Node-RED is a programming development tool for interconnecting hardware and software components, APIs, online services, and has been extensively used on IoT applications [236]. It is a tool designed for programming visually, built on Node.js and developed by IBM. It is a browser-based editor that facilitates programming and simplifies integration. Node-Red allows hardware devices and APIs to be attached, easing the development of applications, and speeding up simulations and deployment of IoT applications [236].

Figure 33 shows snapshots of the data published by the MQTT broker sent to the Smappee cloud and remotely accessible on https://dashboard.smappee.net/board/Antonio'sboard.

Figure 34 shows the Node-RED flow environment interconnecting several nodes. The

Input (phase)	Name	Current	Active power	Reactive power
1 (L1)	S4: lights cct3+4	0.105 A	14.481 W	-20.941 var
2 (L1)	S5-oven+cook ccts5+6	0.059 A	5.653 W	-13.197 var
3 (L1)	S3-cct2-kitchen-garage-2aircon R1+kitc	2.501 A	513.768 W	-313.061 var
4 (L1)	S2-cct1-airConR2,WM	0.182 A	14.182 W	-41.518 var
5 (L1)	Sensor1:mains	6.871 A	1611.373 W	-367.292 var
6 (L1)	Sensor6-boiler	9.616 A	2312.785 W	-20.579 var
7 (L1)	Sensor 7: Pool pump	0.001 A	-0.354 W	-0.105 var
8 (L1)	Sensor8: air con split	0.012 A	0.111 W	-3.064 var

Figure 33: Snapshot from MQTT broker accessed via local network (LAN)

MQTT publisher node is subscribed to a message-topic in the MQTT broker. Other nodes carry data transformation functionalities, and at the end, all consumption data captured by the current sensors is saved in a local file in CSV format. This file contains all the aggregate data for a selected interval (e.g., 1 minute, 15 minutes). This data is then exported to the Blockchain, so machine learning applications can further process it.

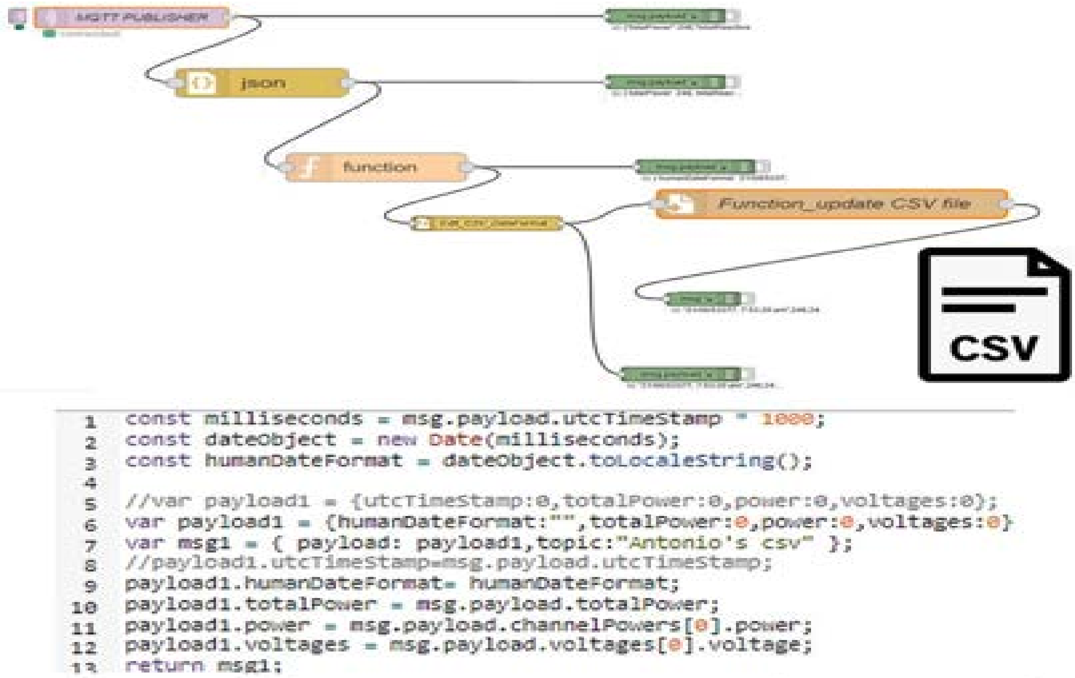


Figure 34: Node-RED set up for automatizing MQTT publishing functionality

3.3.1.2 Simulating a Nanogrid Using an Online Synthetic Data Generator

Whereas the consumption data for a single house is suitable to demonstrate the automation process, it does not allow inferences about *nanogrids* or *microgrids*. To that end, a synthetic data generator was created to simulate real-time consumption data from 11 houses as part of a *nanogrid*. Synthetic data generation enables data scientists to feed machine learning models with data to represent any situation. For instance, synthetic data can be reverse engineered to identify real data, making it ideal for conditional ("*what if*") scenarios. The generation method is artificial using a random scheme and can be a solution when privacy is required. As the data has been used only for simulation and testing purposes, the modifications to the data structure have no impact on the quality and results of this study.

Table 4 shows a sample output (spreadsheet) from a synthetic data generator. At pre-determined intervals (e.g., 10 minutes), a CSV file containing all the consumption events for a group of appliances is created. The last column (Table 4) shows that the use categories are all mixed up and must be aggregated to avoid unnecessary processing power.

DAILY EVENT TABLE - BATCH 17														
Event_Id	Date	Time_24H	Duration_Min	Appl_Id	Appl.NAME	Global_active_power	Global_reactive_power	Voltage	Global_intensity	Total Subm. 1+2+3	Total measure, WH	POWER Composition [kWh]	USE CATEG	CATEGORY NAME (Literal)
[illegible]	[illegible]	[illegible]	22	00010_c2	PrtInkGrkt	2.27	0	234.58	7	0	0	0	E	EDUCATION, COMMS, ENTERTA
[illegible]	[illegible]	[illegible]	3	00021_c9	Pump1_T	0.14	0	231.5	1.6	0	0	0	H	POOL, SAUNA, SPA
[illegible]	[illegible]	[illegible]	27	00021_c8	Pump1_P	1.1	0.1	244.3	4.46	0	0	0	H	POOL, SAUNA, SPA
[illegible]	[illegible]	[illegible]	18	0001_C1	WashMach	2.37	0.37	226.1	9.78	0	0	0	D	MECHANICAL LABOR-SAVING
[illegible]	[illegible]	[illegible]	5	00017_c4	LightLGR123	2.21	0.07	226.74	9	0	0	0	A	LIGHTING
[illegible]	[illegible]	[illegible]	14	00023_c10	A/CA_SP	2.42	0	259.69	10.6	0	0	0	F	SPACE HEATING AND COOLING
[illegible]	[illegible]	[illegible]	11	00014_c2	Microw_Kit	2.32	0.09	226.87	9.78	26	332	0.63	C	COOKING & WATER HEATING
[illegible]	[illegible]	[illegible]	24	00013_c2	Dishw-Kit	2.47	0.19	213	10.29	0	0	0	D	MECHANICAL LABOR-SAVING
[illegible]	[illegible]	[illegible]	23	00010_c2	Appl_Kit	2.26	0.06	231.33	9.25	0	0	0	C	COOKING & WATER HEATING
[illegible]	[illegible]	[illegible]	29	00013_c2	Dishw-Kit	5.46	0.23	247.68	23.88	36	1019	2.02	D	MECHANICAL LABOR-SAVING
[illegible]	[illegible]	[illegible]	10	00014_c2	Microw_Kit	1.28	0	216.34	5.72	0	0	0	C	COOKING & WATER HEATING
[illegible]	[illegible]	[illegible]	6	0009_c2	PowTools	3.49	0.16	228.74	11.94	33	51	0.33	D	MECHANICAL LABOR-SAVING
[illegible]	[illegible]	[illegible]	27	0006_c2	PCs_Gar	3.9	0.05	260.47	8.21	21	448	0.46	E	EDUCATION, COMMS, ENTERTA
[illegible]	[illegible]	[illegible]	24	00016_c3	LightKitR4	2.48	0.05	227.88	10.17	0	24	0.02	A	LIGHTING
[illegible]	[illegible]	[illegible]	11	00015_c6	Oven+Gr	2.97	0.21	210.79	12.27	1	11	0.02	C	COOKING & WATER HEATING
[illegible]	[illegible]	[illegible]	11	0002_c3	TV+VideoLT	4.18	0	230.48	17.86	14	483	0.48	E	EDUCATION, COMMS, ENTERTA
[illegible]	[illegible]	[illegible]	20	0006_c2	PCs_Gar	2.44	0.28	225.07	10.11	0	20	0.02	E	EDUCATION, COMMS, ENTERTA
[illegible]	[illegible]	[illegible]	16	00016_c3	LightKitR4	2.18	0.13	252.82	10.81	1	16	0.02	A	LIGHTING
[illegible]	[illegible]	[illegible]	24	00021_c8	Pump1_P	4.34	0.11	263.77	18.28	27	405	2.42	H	POOL, SAUNA, SPA
[illegible]	[illegible]	[illegible]	14	00012_c2	FridgeKit	2.2	0.05	225.19	9.66	0	0	0	B	FOOD PRESERVATION
[illegible]	[illegible]	[illegible]	12	00010_c5	Cook+Hd	2.12	0.06	216.37	10.19	0	0	0	C	COOKING & WATER HEATING
[illegible]	[illegible]	[illegible]	3	00011_c2	Appl_Kit	3.02	0.21	227.61	14.1	29	116	0.23	C	COOKING & WATER HEATING
[illegible]	[illegible]	[illegible]	11	00024_COMP	Under	0.19	0.11	254.29	1.7	1	17	0.06	U	UNDEFN

Table 5: Consumption Data for a single house

Table 5 displays the same data consumption, however, data has been aggregated by the use categories. On each pre-determined interval, a snapshot is taken, including all the events for each category: (a) Lighting, (b) Food preservation, (c) Cooking and water heating, (d) Labour-saving and mechanical tools, (e) Education, communication, gaming (f) Space cooling and heating, (g) Hygiene, (h) Outdoor entertainment, and (j) Electrical vehicles.

Event_Id	Date	Time_24H	Duration_Min	Appl_Id	Appl.NAME	Global_active_power	Global_reactive_power	Voltage	Global_intensity	Total Subm. 1+2+3	Total measure, WH	POWER Composition	USE CATEG	CATEGORY NAME (Literal)
41663	17/12/2011	6:13:10	3	0001T_c4	LightLGR123	0.33	0.106	244.62	1.8	1	3	0.003	A	LIGHTING
41640	17/12/2011	5:51:38	3	0001T_c4	LightLGR123	2.184	0	244.59	9.2	0	0	0	A	LIGHTING
41677	17/12/2011	6:28:30	7	00016_c3	LightKitR4	1.42	0.098	244.93	7	2	14	0.014	A	LIGHTING
41673	17/12/2011	6:25:14	15	00016_c3	LightKitR4	2.784	0.086	243.65	11.4	1	15	0.015	A	LIGHTING
41656	17/12/2011	6:07:01	15	0001T_c4	LightLGR123	2.44	0.11	243.7	10	2	30	0.03	A	LIGHTING
41657	17/12/2011	6:08:25	28	0001T_c4	LightLGR123	2.426	0.082	243.53	9.8	2	56	0.056	A	LIGHTING
41608	17/12/2011	5:19:44	1	00016_c3	LightKitR4	1.926	0.136	244.33	8.8	0	0	0	A	LIGHTING
41642	17/12/2011	5:53:06	23	0001T_c4	LightLGR123	1.32	0	245.71	8.6	0	0	0	A	LIGHTING
41690	17/12/2011	6:40:15	13	0001T_c4	LightLGR123	0.634	0.136	244.35	3	0	0	0	A	LIGHTING
41665	17/12/2011	6:16:28	16	00012_c2	FridgeKit	2.406	0.076	242.91	9.8	1	16	0.032	B	FOOD PRESERVATION
41615	17/12/2011	5:26:31	15	00012_c2	FridgeKit	2.462	0.098	245.16	10	0	0	0	B	FOOD PRESERVATION
41596	17/12/2011	5:06:01	29	0005_c2	FridgeBsr	2.02	0	243.62	9.2	18	522	1.044	B	FOOD PRESERVATION
41632	17/12/2011	5:43:16	22	0005_c2	FridgeBsr	2.312	0.046	242.51	9.6	0	0	0	B	FOOD PRESERVATION
41669	17/12/2011	6:20:34	23	0005_c2	FridgeBsr	2.414	0.08	242.63	9.8	1	23	0.058	B	FOOD PRESERVATION
41673	17/12/2011	6:24:48	20	0005_c2	FridgeBsr	2.428	0.094	243.66	9.8	1	20	0.04	B	FOOD PRESERVATION
41604	17/12/2011	5:15:21	21	0005_c2	FridgeBsr	3.486	0.054	242.45	14.2	19	399	0.798	B	FOOD PRESERVATION
41599	17/12/2011	5:09:40	22	00012_c2	FridgeKit	3.374	0.046	240.82	14	17	374	0.748	B	FOOD PRESERVATION
41602	17/12/2011	5:12:06	5	0005_c2	FridgeBsr	1.634	0.07	242.93	6.4	18	90	0.18	B	FOOD PRESERVATION
41685	17/12/2011	6:39:20	30	0005_c2	FridgeBsr	0.738	0.116	244.02	3.2	1	30	0.06	B	FOOD PRESERVATION
41622	17/12/2011	5:32:26	12	00012_c2	FridgeKit	2.332	0	242.67	9.6	1	12	0.024	B	FOOD PRESERVATION
41624	17/12/2011	5:34:43	13	0001I_c2	Appl_Kit	0.224	0	244.96	1	0	0	0	C	COOKING & WATER HEATING
41644	17/12/2011	5:54:52	12	00020_c7	HW_Boiler	2.164	0.098	244.63	9.2	0	0	0	C	COOKING & WATER HEATING
41674	17/12/2011	6:24:28	14	00013_c6	Oven+Gr	2.582	0.092	244.02	10.6	2	28	0.056	C	COOKING & WATER HEATING
41672	17/12/2011	6:23:05	2	00014_c2	Microw_Kit	2.352	0.088	243.36	9.8	2	4	0.008	C	COOKING & WATER HEATING
41636	17/12/2011	5:46:41	28	00014_c2	Microw_Kit	2.302	0.05	242.22	9.4	0	0	0	C	COOKING & WATER HEATING
41671	17/12/2011	6:22:10	22	00010_c5	Cook+Hd	0.312	0.112	245.05	1.6	1	22	0.044	C	COOKING & WATER HEATING
41679	17/12/2011	6:30:38	2	00014_c2	Microw_Kit	3.194	0.068	242.05	13.2	0	0	0	C	COOKING & WATER HEATING
41659	17/12/2011	6:09:51	28	0001I_c2	Appl_Kit	0.43	0.106	244.39	2.8	2	56	0.112	C	COOKING & WATER HEATING
41626	17/12/2011	5:37:39	22	00013_c6	Oven+Gr	2.33	0	242.56	9.6	0	0	0	C	COOKING & WATER HEATING
41684	17/12/2011	6:35:43	12	0001I_c2	Appl_Kit	0.592	0.128	245.39	2.6	0	0	0	C	COOKING & WATER HEATING
41650	17/12/2011	6:00:33	17	00013_c6	Oven+Gr	2.076	0.206	244.36	9.2	0	0	0	C	COOKING & WATER HEATING
41595	17/12/2011	5:06:26	4	00014_c2	Microw_Kit	1.326	0	244.66	5.6	18	72	0.144	C	COOKING & WATER HEATING
41597	17/12/2011	5:06:11	7	00014_c2	Microw_Kit	3.378	0.056	241.41	14	18	126	0.252	C	COOKING & WATER HEATING
41598	17/12/2011	5:08:59	15	00013_c6	Oven+Gr	3.372	0.054	240.91	14	19	285	0.57	C	COOKING & WATER HEATING
41605	17/12/2011	5:16:09	3	0001I_c2	Appl_Kit	2.91	0.056	243.69	12	9	27	0.054	C	COOKING & WATER HEATING
41686	17/12/2011	6:37:25	12	00010_c5	Cook+Hd	0.82	0.126	245.04	3.4	0	0	0	C	COOKING & WATER HEATING
41623	17/12/2011	5:34:28	24	00013_c6	Oven+Gr	2.242	0.046	243.03	9.2	0	0	0	C	COOKING & WATER HEATING
41613	17/12/2011	5:23:12	28	0001I_c2	Appl_Kit	0.624	0.126	246.26	2.6	0	0	0	C	COOKING & WATER HEATING
41614	17/12/2011	5:25:40	2	00010_c5	Cook+Hd	0.716	0.128	246.23	4.4	0	0	0	C	COOKING & WATER HEATING
41616	17/12/2011	5:26:24	30	00020_c7	HW_Boiler	2.46	0.1	244.25	10	1	30	0.06	C	COOKING & WATER HEATING
41610	17/12/2011	5:20:30	16	00010_c5	Cook+Hd	1	0.112	243.77	1.8	0	0	0	C	COOKING & WATER HEATING
41652	17/12/2011	6:03:38	27	00013_c6	Oven+Gr	2.118	0.204	243.95	9.2	0	0	0	C	COOKING & WATER HEATING
41651	17/12/2011	6:02:14	21	00014_c2	Microw_Kit	0.402	0.236	245.77	1.8	0	0	0	C	COOKING & WATER HEATING
41641	17/12/2011	5:52:47	24	00014_c2	Microw_Kit	2.36	0	245.62	9.6	1	24	0.048	C	COOKING & WATER HEATING
41668	17/12/2011	6:19:54	24	0001_C1	WashMach	2.832	0.084	242.41	10	2	48	0.048	D	MECHANICAL LABOR-SAVING
41666	17/12/2011	6:17:51	29	0009_c2	PowTools	2.442	0.096	242.04	10	2	58	0.058	D	MECHANICAL LABOR-SAVING
41648	17/12/2011	5:59:18	24	0009_c2	PowTools	2.166	0.206	244.29	9.2	0	0	0	D	MECHANICAL LABOR-SAVING
41646	17/12/2011	5:56:21	16	0009_c2	PowTools	2.026	0.212	245.16	9	0	0	0	D	MECHANICAL LABOR-SAVING
41594	17/12/2011	5:04:53	12	00013_c2	Dishw-Kit	2.934	0.05	243.77	12.6	19	228	0.228	D	MECHANICAL LABOR-SAVING
41637	17/12/2011	5:48:57	25	0001_C1	WashMach	2.324	0	242.6	9.6	0	0	0	D	MECHANICAL LABOR-SAVING
41635	17/12/2011	5:46:21	22	0009_c2	PowTools	0.664	0	249.55	5.6	1	22	0.022	D	MECHANICAL LABOR-SAVING

Table 4: Data categorisation per usage

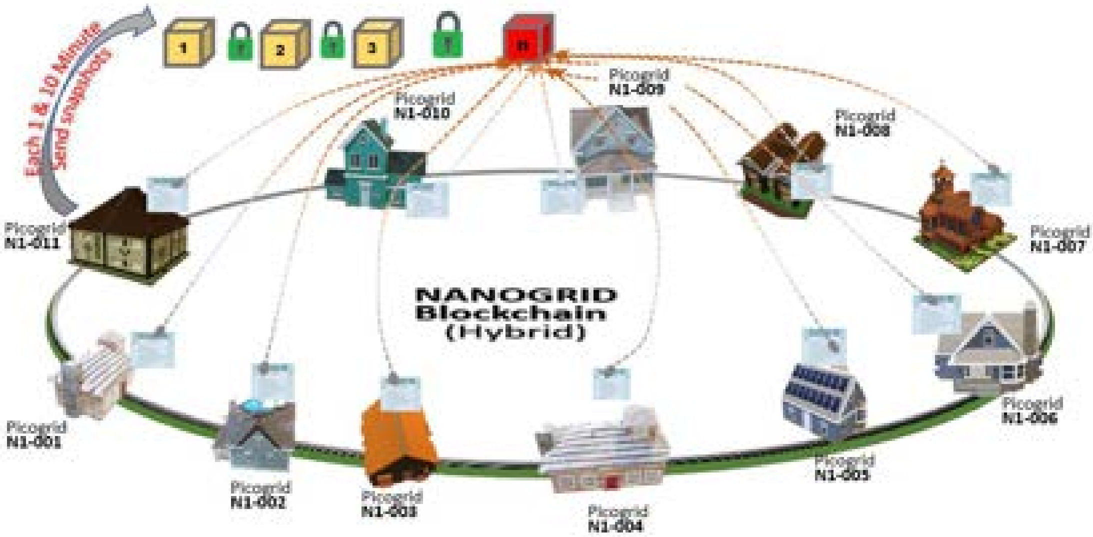


Figure 35: Hybrid Nanogrid Blockchain receiving data from each picogrid

BAIoT creates snapshots on established intervals for each house in the same format (CSV) and data structure and sends its results to the Blockchain. The information is encrypted and only accessible by authorised applications, controlled via the consensus protocol.

Figure 35 & 36 show a hybrid Blockchain network with 11 houses, sending individual snapshots summarizing all the consumption for 10 minutes. Figure 38 shows data snapshots from each house classified by use categories.

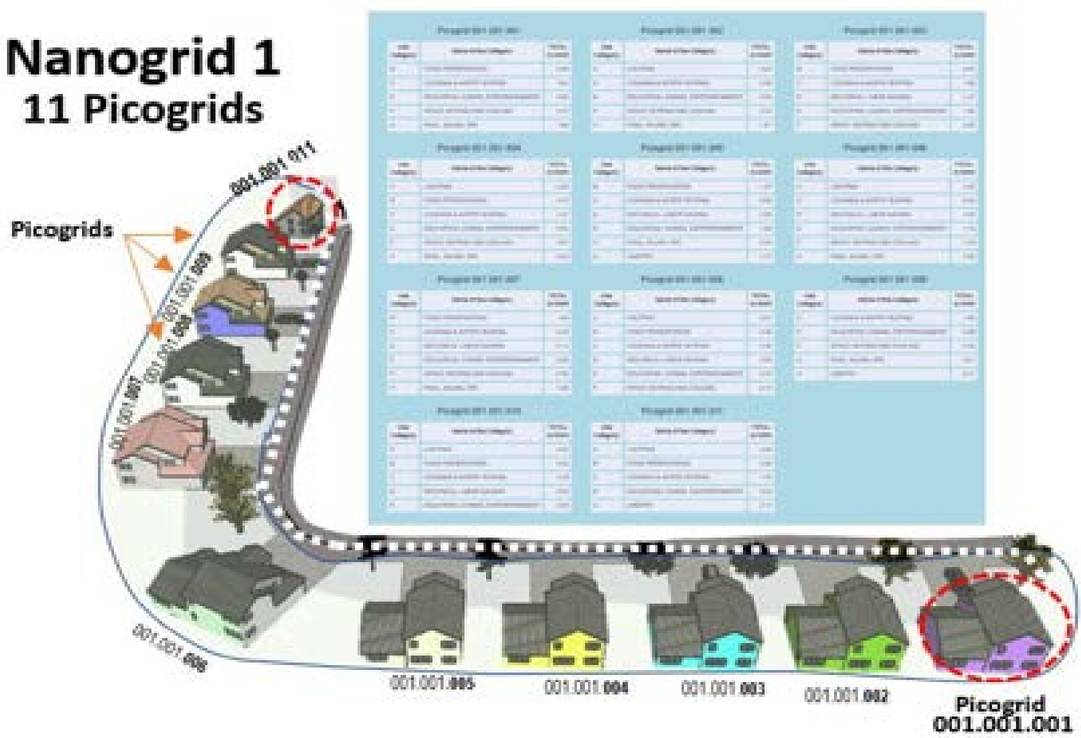


Figure 36: Nanogrid with 11 houses and respective data snapshots exported to the Blockchain

3.3.2 Data Acquisition for the Comparative Case Study (Using ML models)

Forecasting power supply, demand, and storage are foundational requirements for small-scale autonomous power plants since they are small and must always find the balance between supply and demand. Since power autonomy and sustainability are the ultimate goals, forecasting becomes crucial for optimising consumption, anticipating issues, and helping the user to make informed decisions.

The comparative case study is used to create knowledge and improve the understanding of how well machine learning (ML) models can predict power consumption. ML can enable a range of proactive actions to compensate for the lower resilience of small-scale and decentralised power plants depending on how it is deployed.

Several data sets have been released to provide reliable disaggregated data for power appliances and buildings in recent years. Among the most well-known includes Enertalk [339] (Korea), DRED [340] (Netherlands), REDD [341] (USA), REFIT [342] (UK) and Dataport [343] (USA). Power load disaggregation refers to the process of separating (or classifying)

Table 6: snapshot from the first block in the Blockchain ledger

Block Nr	000001	Timestamp (DD-MM-YYYY HH:MM:SS) 27/07/2020 9:44:32 AM	
PREVIOUS HASH	f6B3b9b2a69fe1c0440399f38d94b3871714dcbae6c8193a2ba5a29		
Picogrid Nr	CAT	Power [W]	Picogrid Hash Consumption Hash
001.001.001	**Total**	**4561**	**55399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2bb9b2a69fe1c0**
001.001.001	A	611	73987171b447275a29978a4dcbae6c8193a2bb9b2a69fe1c0440399fa0f138d9
001.001.001	B	559	57614dcbae6c8193a2bb9b2a69fe1c0440399f38d94b3a0f1b447275a29978a8
001.001.001	C	139	841b2a69fe1c0440399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2
001.001.001	D	924	5238193a2bb9b2a69871714dcbae6cfe1c0440399f38d97275a29978a4b3a0f1
001.001.001	E	752	866b447275a29978a871714dcbae6c8193a2bb9b2a69fe1c0440399f38d94b3a
001.001.001	F	769	117b9b2a69fe1c0440399f38d94b3871714dcbae6c8193a2ba5a29978a0f1b44
001.001.001	G	764	1811c0440399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2bb9b2a6
001.001.001	H	43	4602bb9b2a69fe1c0440399f38d94b3a0f1b447275a29978a871714dcbae6c81
001.001.002	**Total**	**4066**	**1568193a2bb9b2a69871714dcbae6cfe1c0440399f38d97275a29978a4b3a0f1**
001.001.002	A	135	415e1c0440399fb9b2a69f38871714dcbae6c8193a2bd94b3a0f1b447275a299
001.001.002	B	194	51999f38d94b3a0f1b447275a29978a871714dcbae6c8193a2bb9b2a69fe1c04
001.001.002	C	782	9539fe1c0440399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2bb9b
001.001.002	D	924	954b9b2a69fe1c0440399f38d94b3871714dcbae6c8193a2ba5a29978a0f1b44
001.001.002	E	856	4191c0440399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2bb9b2a6
001.001.002	F	236	6282bb9b2a69fe1c0440399f38d94b3a0f1b447275a29978a871714dcbae6c81
001.001.002	G	518	47399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2bb9b2a69fe1c0
001.001.002	H	421	554b2a69fe1c0440399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2
001.001.003	**Total**	**3894**	**537e1c0440399fb9b2a69f38871714dcbae6c8193a2bd94b3a0f1b447275a299**
001.001.003	A	385	90314dcbae6c8193a2bb9b2a69fe1c0440399f38d94b3a0f1b447275a29978a8
001.001.003	B	406	700b2a69fe1c0440399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2
001.001.003	C	143	5138193a2bb9b2a69871714dcbae6cfe1c0440399f38d97275a29978a4b3a0f1
001.001.003	D	814	783b447275a29978a871714dcbae6c8193a2bb9b2a69fe1c0440399f38d94b3a
001.001.003	E	921	94b9b2a69fe1c0440399f38d94b3871714dcbae6c8193a2ba5a29978a0f1b44
001.001.003	F	652	6651c0440399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2bb9b2a6
001.001.003	G	300	4482bb9b2a69fe1c0440399f38d94b3a0f1b447275a29978a871714dcbae6c81
001.001.003	H	273	912399f38d94b3a0f1b447275a29978a871714dcbae6c8193a2bb9b2a69fe1c0
001.001.004	**Total**	**3823**	**415e1c0440399fb9b2a69f38871714dcbae6c8193a2bd94b3a0f1b447275a299**

the energy consumption per individual appliance. The non-intrusive load monitoring (NILM) methods have become popular over the last decade and typically use signal processing and machine learning models [344]. NILM can help identify major energy guzzlers by referring to the measurements collected from a single point, usually placed at the switchboard.

Some of these data libraries only cover a limited number of houses, have a limited data collection period, or have a low number of appliances, making them unsuitable for this particular study. After several considerations around using locally acquired versus third-party data, consistency, and dependability aspects, it was decided to use the Dataport libraries [343]. Dataport datasets have been extensively used in hundreds of academic research studies. Pecan Street Inc is a research US company based in Austin, Texas. It has been collecting power consumption data for over six years, including 1,115 homes and businesses [345] and making it available for registered customers, including many universities worldwide. Historical power consumption data, metadata reports, and data dictionaries have been obtained from Dataport via a user license agreement between Pecan Street Inc and registered university students [338].

As shown in *Table 7*, in total, assorted data for 73 houses have been acquired between 2014 and 2019; 25 houses in Austin (Texas) were collected in 2018; 25 in upstate New York between May and October 2019; and 23 houses in California in varied periods, between 2014 and 2018. All data are anonymised from volunteer participants. The frequency of data collection varied between 15-minute, 1-Minute and 1-second intervals. Metadata containing climate data and site details (e.g., house size, location.) were combined with the consumption data.

	Interval / Frequency	Nr. Houses	Period	Year
Texas	- 1-Second - 1-Minute - 15-Minutes	25	1 year	2018
New York	- 1-Second - 1-Minute - 15-Minutes	25	6 months	2019
California	- 1-Second - 1-Minute - 15-Minutes	23	1 year	2014-2018

Table 7: Data acquired from Dataport libraries

3.3.2.1 **Defining and Selecting the Cases**

From a total of 18 possible scenarios, only six cases have been considered from a practical standpoint. The goal was to prioritise the cases that could provide the most significant outcome when considering data sizes, frequency collection, computational cost, timing, and accuracy.

Case 1: A *microgrid* with 73 houses and data collection at a 15-minute interval

Case 2: A *nanogrid* with 25 houses and data collection at a 15-minute interval

Case 3: A *nanogrid* with 25 houses and data collection at 1-minute interval

Case 4: A *picogrid* (house) and data collection at a 15-minute interval

Case 5: A *picogrid* (house) and data collection at a 1-minute interval

Case 6: A *picogrid* (house) and data collection at a 1-second minutes interval

The results of the comparative case study are presented in Chapter 6 of this study.

3.3.2.2 AI/ML tool selection

Data Science Studio (DSS) is a predictive modelling tool from Dataiku, and it has been selected to support the decision-making process for the BAIoT-ADCX models. All the time series associated with this experiment contain labelled data, implying that a supervised

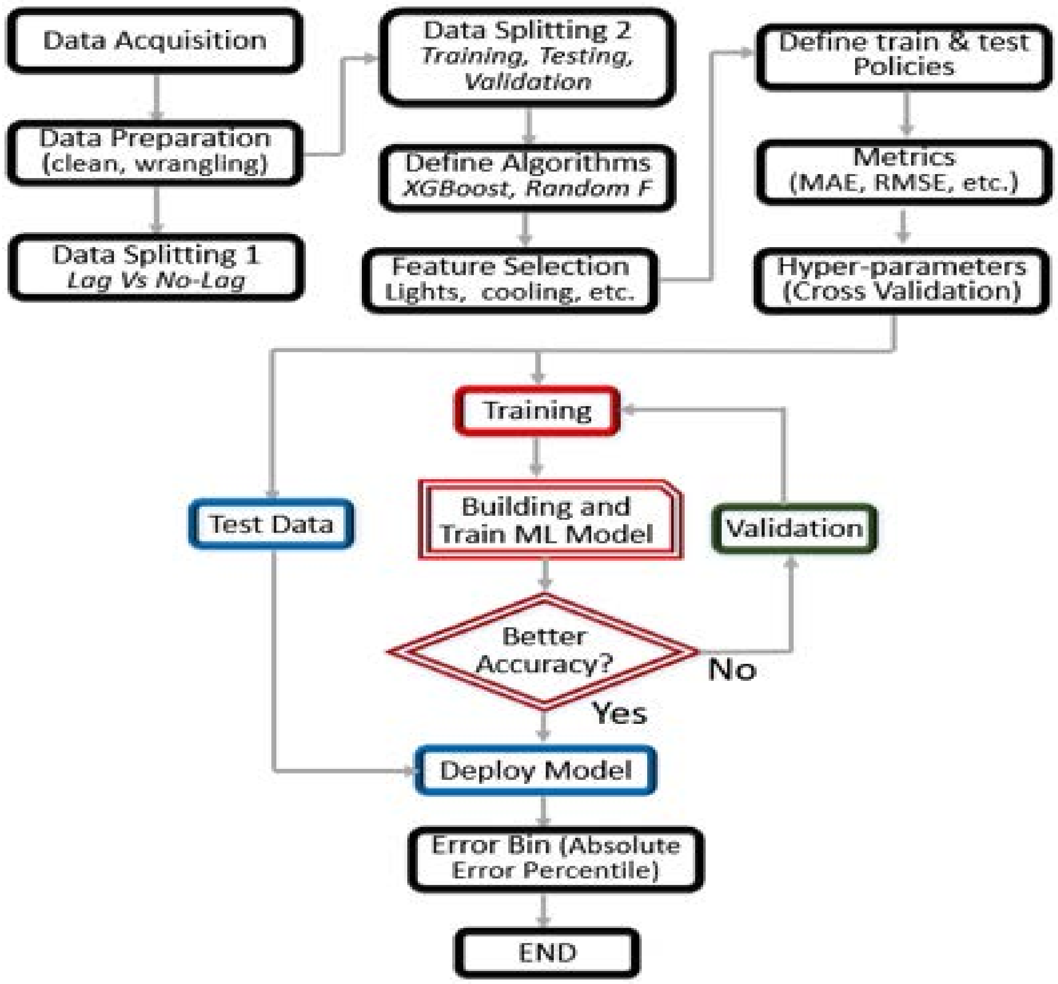


Figure 37: Overall life cycle for the ML model deployed in the comparative case study

learning model is required. DSS computation engine runs locally in a Linux Ubuntu (version 20.04) environment. The method uses historical consumption data, weather, house sizes, and location to predict future demand and power requirements. All the inputs & outputs are numeric values. DSS offers a variety of embedded algorithms for predictive tasks, and the user may tailor or bring extra systems to incorporate into the model.

3.3.2.3 Data Processing

The overall life cycle ML modelling for all the six cases is summarised in Figure 40. Deploying machine learning (ML) in a household for energy consumption prediction involves three stages: (a) collecting data from the appliances, (b) preparing and structuring the original data to extract features, and (c) training the model. During the training stage, the ML model learns the patterns, evaluates the accuracy, and validates the pre-trained model by validation samples. After being trained and validated, the prediction model can be used in real time, in real case scenarios (production), for forecasting power consumption.

3.3.2.4 Data Cleansing & Preparation

Fourteen time-series datasets with electrical consumption data have been extracted from Dataport libraries, with 52 columns, including several appliance types, solar photovoltaic power, electrical vehicles data, and house ID. Data transformations, merging, parsing, wrangling, and cleaning occur, and outliers and inconsistencies are all removed.

After cleaning, merging the metadata, and all data transformations in place, it was possible to reduce from 52 to 25 columns - and applied to all the datasets.

3.3.2.5 Target Variable & Feature Selection

The total consumption for all appliance categories (A through G) has been chosen as the target variable for this experiment. Seeking to keep consistency across all scenarios, only those features that impacted results the most were selected, as indicated in *Table 8:*

FEATURE HANDLING		STATUS
#dataID	House identifier (Picogrid #)	Rejected, too many equal values
#localminute	Original Timestamp	**Reject**
#localminute_Parsed	Parsed Timestamp (ISO 8601)	**Reject**
#date	DD/MM/YYYY	**Reject**
#time	HH:MM:SS am/pm	**Reject**
#day_since_started		**Reject**
#app_Total_A_B_C_D_E_F_G	Total Consumption All Femtogrids	**TARGET VARIABLE**
#lights_A	Consumption sum for all the lights	ON
#food_preserv_B	Consumption Sum for fridges, freezers, coolers	ON
#cooking_C	Consumption Sum of all kitchen applicancs	ON
#mechanical_labor_sav_D	Sum of all mech labor appl.	ON
#Space_cooling_heating_F	Sum of all air-conditioners/heating un	ON
#higiene_G	Consumption Sum of all bathrooms	ON
#electrical_vehicle_J	Consumption Sum of all electr. Vehicles	Rejected, too many equal values
#renewable_energy	Sum of power generation for renewables	ON
#grid	Power from utility service provider	**Reject**
#TAVC_C (temp avg Celsius)	Average Temperature in Celsius	ON
#TMAX_C	Maxime Temperature in Celsius	ON
#TMIN_C	Minimum Temperature in Celsius	ON
#building_type	Type of building (house, flat, etc.)	Rejected, too many equal values
#city	City area where house is located	Rejected, too many equal values
#LAT	Latitute	Rejected, too many equal values
#LONG	Longitude	Rejected, too many equal values
#house_constr_year	House Construction Year	ON
#total_SQMT	House size in square meters (SQMT)	ON

Table 8: Target Variable & Feature Selection

3.3.2.6 Algorithms Selection

Different ML algorithms search for different trends and patterns. No algorithm may perform reasonably across all use cases, and finding the best solution involves trials and parameters (and hyperparameters) tuning. Since the main task is prediction, and the target variable is a numeric value, the algorithms selected are depicted in Figure 38.

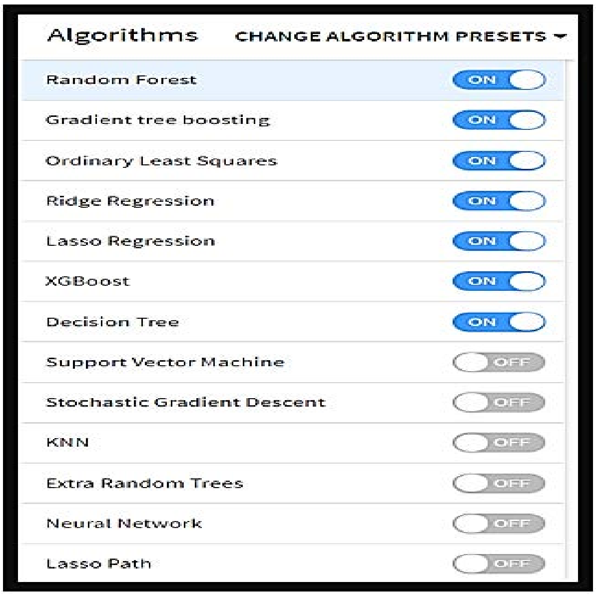


Figure 38: Algorithms selected in this study

3.3.2.7 Error Metrics

Mean Absolute Error (MAE) has been selected as the preferred method for error metrics since outliers do not severely impact it. RMSE (Root Mean Square Error) has been used in some cases for comparison reasons.

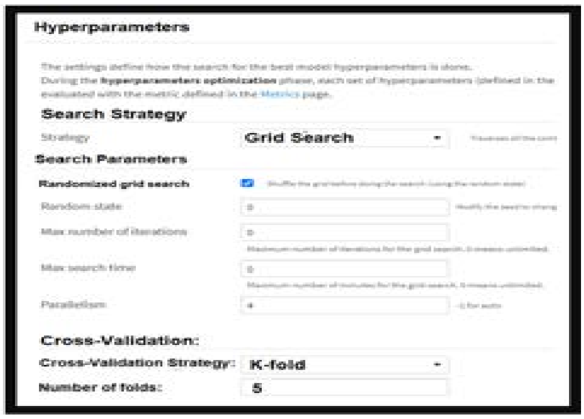


Figure 39: Hyperparameters

3.3.2.8 Model Hypermeters Tuning

The Hyperparameter settings define how the MLengine search and represents the best strategies, e.g., grid, random or Bayesian searches. During the hyperparameter optimisation phase, each hyperparameter renders the selected algorithms and then cross-references with the metrics established (MAE, in this case). In this experiment, *Grid Search* has been selected. The metrics used to rank hyperparameter points are computed by cross-validation, and 5-fold cross-validation has been selected. In K-fold cross-validation, the data is split into k subsets and the process is then repeated k times, once for each fold defined in the validation set.

3.3.2.9 Train and Test Policy for Final Evaluation

The train/test split policy used in the DSS tool was '*explicit extracts from two datasets'*, one for training and one for the test. For the dataset for the *picogrids* @ 1-sec intervals, the number of records was very large (e.g., 15-million rows), and then the sampling method was used. In both sets, train and test, random sampling with a ratio of 20% was selected. As for the datasets with lower than 2 million rows, it was chosen to train the whole dataset and no sampling.

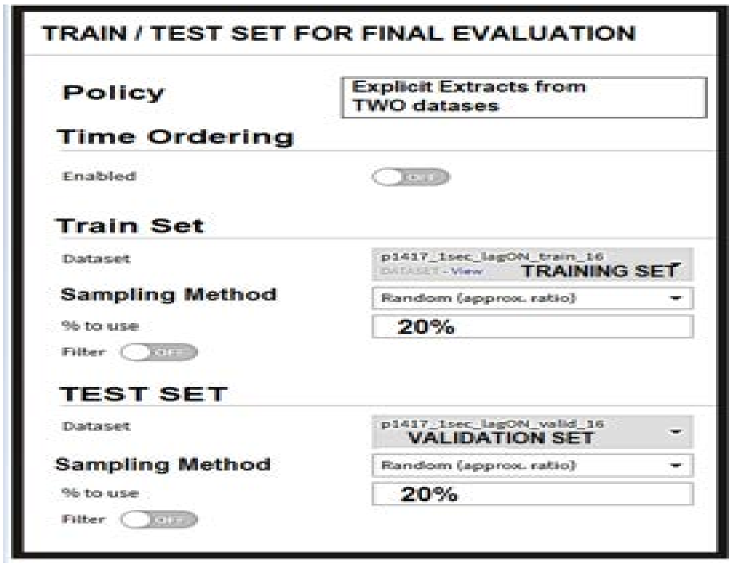


Figure 40: Train & Test Policy settings

Chapter 4: An Exploratory Study on the Causes, Sources, Drivers, and Root Causes of Global Greenhouse Gases (GHG) Emissions

Abstract: Misconceptions are widespread in understanding global greenhouse gas (GHG) emissions, causing confusion and helping perpetuate the problem. There is a gigantic gap between the perception of the consumers and the harsh realities of power producers, especially in the electricity industry. Whereas some developed nation-states claim some slight achievement in transitioning to renewable sources, the global greenhouse gas emissions keep rising persistently, despite the Covid-19 period. As it stands, no credible inferences can be made about renewable sources' effectiveness in contributing to lowering emissions. The misinformation helps existing stakeholders to buy extra time while the situation worsens. Whereas there is no global authority and no regulation enforcing emissions reduction, the emissions problem worsens. This study explores the several ramifications of the global emissions associated with the production of electricity and fossil fuels and the free-riding institutions which either stimulate or facilitate the continuation of the status quo. It helps eliminate myths and improve understanding of emissions' key factors. Raising awareness of the causes, sources, drivers, and root causes of greenhouse gas emissions (GHG) is a pre-requirement for drawing a solution to reduce or stabilise the problem.

4.1 Introduction

Real economic growth of less than 2% annually is considered stagnation for developed economies, whereas people have assimilated high carbon lifestyles. Great recessions occur when financers do not perceive fair chances of recovering their funds within a short period (e.g., a few decades), usually followed by a period of high unemployment, inflation and recession. So, continuous GDP growth is the crucial *fuel* that keeps all the financial and government machines running smoothly. High GDP growth means low risk to investors, higher productivity rates, and more consumption, which translates to higher funds for governments and their affiliates. The higher the stimulation of the consumers, the higher the emission levels.

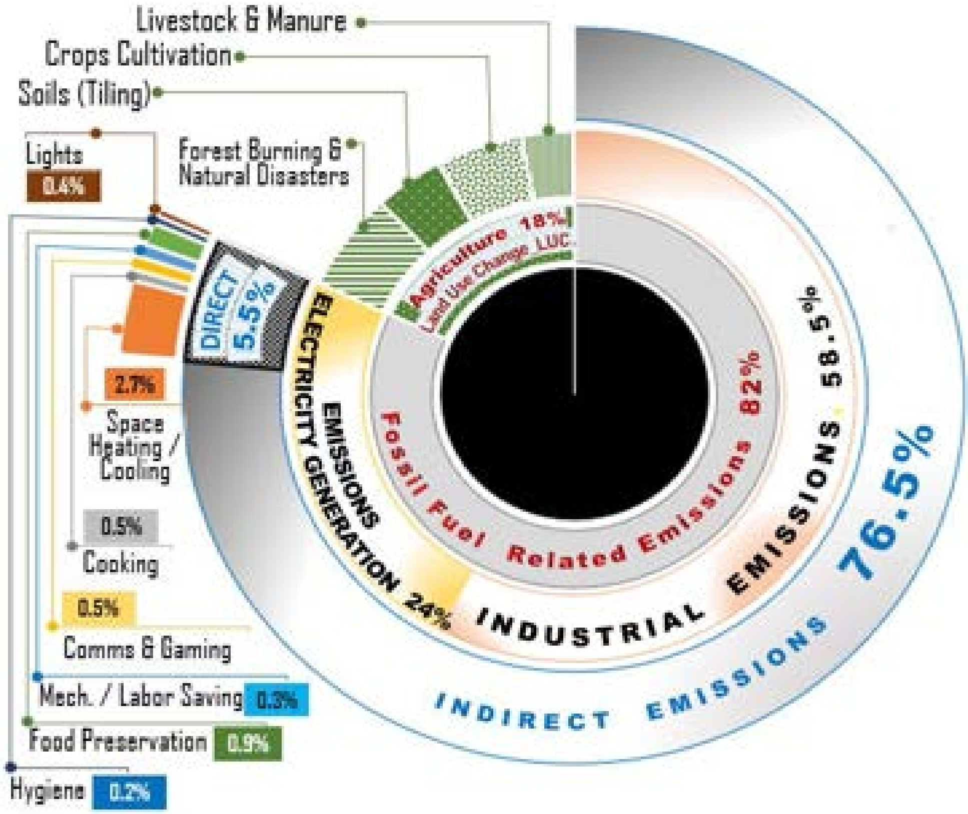


Figure 41: Direct Householder Emission (5.5%), Indirect

Strong evidence confirms the historical relationship between GHG emissions and economic growth [346, 347, 348, 349, 350]. Finding a solution to mitigate global emissions implies finding answers aligned with governments, corporations, communities, individual needs, and desires. Since governments have become extremely dependent on local corporations (for income), they no longer hold the bargaining power to impose extra costs on production processes. Releasing emissions directly into the atmosphere is far less costly than deploying complex mechanisms to mitigate the emissions problem. While global commons remain unmanaged, nation-states encourage local corporations to increase productivity. While global emissions keep rising in a quasi- exponential trend, the public has been distracted by pledges and ineffective propositions to mitigate climate change.

4.1.1 Direct, Indirect, Embodied, and Embedded Emission

Indirect emissions happen in the background without the involvement of the user (individuals or organisations); It may refer to the extraction or fracking minerals in mining, use of fertilizers in crop plantation, use of cement and steel in construction and manufacturing processes, transportation and more. The users trigger indirect emissions when they acquire more goods and services. Around 82% of the global emissions are related to fossil fuels and 18% by land-use change GHG emissions [351]. Most of it (~76.5%) are indirect emissions (Figure 41), where 24% refers to the production of electricity and 58.5% to industrial emissions. Apart from burning natural gas for cooking (or heating water), the direct emissions from householders emissions represent 5.52% of the global emissions (daily operations, power appliances). These findings were collected through 430 journal publications worldwide in 2020 [352]. So, most consumers only have a vague notion of indirect emissions - they have very low visibility of background processes for extracting raw materials, manufacturing products, generating electricity, and producing consumables.

Embedded emissions refer to the release of gases associated with goods - arising from the production process. Depending on the context, embedded emissions and embodied emissions may be interchangeable. It is generally for establishing carbon accountability for importing and exporting goods. Currently, these emissions are assigned to the countries where the goods are produced, although it has been argued that they should be assigned to the importing countries. Estimates of embedded emissions from international trades vary between 20 and 30% of the global carbon emissions [353].

Embodied emissions are often associated with total emissions released in a building before the operations stage, e.g., for all materials and services before and during the construction. Mining, exploring, drilling raw materials, transformation processes, industrialisation, refinement, transportation, and disposal of solid waste, can all yield embodied GHG emissions. A term variant is embodied energy, the sum of all the energy required to produce any service or goods that are incorporated in the product during its creation or manufacturing process. In contrast, operational emissions are related to the daily consumption in a building, such as electricity and gas.

Considering a typical brick veneer house with a 50 years lifespan, the initial embodied energy accounts for 47% of the total energy. That includes all the materials and services before operations. Then, 20% is estimated for the recurrent embodied energy (for repairs and maintenance), and 33% refers to its operational consumption [354, 355, 356]. There is a range of databases for quantifying the embodied energy of goods, materials, services, and products. Melbourne University developed the EPiC, UNSW developed the ICM database, and IPTS developed EEIO tables for Europe [357, 358, 359]

4.1.2 UNDERSTANDING THE TYPE OF GASES AND THEIR POTENTIAL IMPACT

There are four categories of gases that most contribute to the GHG effects: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases [360]. GHG concentration has risen steadily for all types of gases [361, 362, 363, 364, 365] (Figure 42).

CO_2 emissions account for 65% of the total releases of GHG gases [360] and can remain in the environment for hundreds of years. However, it can be difficult to determine the exact lifespan since reactions and processes can happen and remove CO_2 from the atmosphere. Carbon dioxide is mostly emitted by industrial processes, such as fossil fuel burnings, transportation, or agriculture-related activities. It can be human-induced direct through land use, forestry, deforestation, land clearing, and soil degradation. Conversely, soil vegetation can capture CO_2 from the atmosphere over replanting, soil treatment, and other activities [366].

Methane gas (CH_4) is the second most potent GHG and can last about 12 years in the atmosphere. It can be about 30 times more potent over 100 years, accounting approximately for 16% of the total GHG emissions. CH_4 can be "biogenic", emitted by plants and animals, or produced from "fossil", and can be kept beneath land or the ocean for millions of years [367]. Methane is largely emitted from producing and transporting coal, natural gas and oil - as well as in agricultural activities, such as livestock farming, from the digestive systems of grazing animals (ruminants). However, more recent studies suggest that the "*extraction*

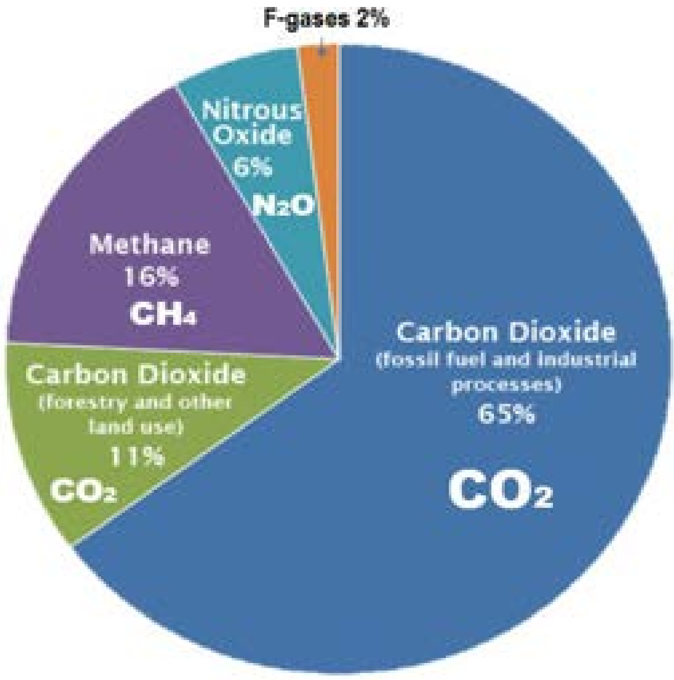


Figure 42: Global Emission by type of Gases - Source: IPCC 5th Assessment, WGIII, 2014

and use of fossil fuels may have been severely underestimated" [362].

Nitrous oxide (N_2O) is a powerful GHG known as the laughing gas. Fertilisers release N_2O as part of the food production chain, fossil fuel combustion, manure, and the burning of agricultural residues. N_20 concentration rate in the atmosphere has been increasing at 2% per decade. The recent growth indicates an urgency to mitigate N_2O emissions [368]. Once emitted, N_20 can persist in the air for longer than 100 years. When integrated over 100-year (for comparison purposes), it is considered 298 times as effective as CO_2 [364].

Fluorinated gases (F-gases), or industrial gases, are used as refrigerants or solvents in manufacturing processes. It can occur as fugitive emissions of a variety of consumer products such as perfluorocarbons (PFCs), nitrogen trifluoride (NF3), hydrofluorocarbons (HFCs), and sulphur hexafluoride (SF6). Fluorinated gases account for about 2% of the global GHG emissions and can have heat-trapping potential of thousands of times greater than CO_2 and stay in the atmosphere for thousands of years [366].

4.1.3 CARBON FOOTPRINT, GHG FOOTPRINT

Carbon footprint is a loose term referring to the amount of greenhouse gases produced to support human activities, expressed in carbon dioxide equivalent (CO2-e) [369, 370]. It is supposed to include the total emission of an entity (object, building) or activity during its entire lifecycle, embodied, operational, and disposal; however, definitions may vary in context and time.

The term operational emissions are commonly found in the literature [371, 372] and may include direct and indirect emissions. Any action, object, service, process, individual, an entire population, a facility (house, factory, commerce), a region (city, suburb, group of countries), or an event (e.g., a trip, a party) has a carbon footprint and therefore operational emissions. The expression *GHG footprint* is also found in the literature with a similar meaning.

There are various resources and methods for estimating the carbon footprints of businesses, organisations, or individuals, such as the Greenhouse Gas Protocol, GHGP [373], from the WRI (World Resources Institute) and the WBCSD (World Business Council for Sustainable Development), and ISO 14064. Several organisations, such as EPA (Environmental Protection Agency, USA), The Nature Conservancy [374], and British Petroleum [375]

Figure 43: Greenhouse Gas (GHG) Footprints

developed their own versions. These calculators allow users to estimate and compare carbon footprints with the world or territorial averages.

The standardised GHG intensity metrics and equivalencies for daily activities [376, 377] allow organisations to create carbon footprint calculators [378]. Many organisations offer online versions of these calculators - some can be sophisticated and serve as anchors to promote their business [379, 380, 381]. It supposes to trigger users to improve behaviours.

The REAP Petite is a domestic type of carbon footprint calculator allowing users to evaluate their emissions and compare them with other consumers. Moreover, it also allows users to set their targets to motivate a reduction in consumption and helping to mitigate emission impacts. It supposes to trigger users to improve behaviours. REAP Petite uses a bottom-up approach, first calculates the individual impact to better estimate the entire household footprint [382]. GHGCal can calculate Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O) emissions from the activities of an organisation [383].

4.1.4 EMISSIONS AS A GLOBAL PROBLEM, NOT A DOMESTIC AFFAIR

When a country (or an organisation) releases GHG emissions, it affects the entire planet as gas molecules disperse, react, re-mix, absorb and are absorbed by other compounds. It spreads beyond original geographical boundaries and may last in the atmosphere for hundreds of years - implying that GHG emissions are a global problem and cannot be solved by domestic policies. Given that global emissions keep rising steadily and despite controversial messages from daily media and agencies, it is fair to assert that existing domestic policies have contributed far more to worsening the global emission problem than mitigating it.

So far, all top-down solutions spearheaded by governments to mitigate global emissions have utterly failed. Global emissions trade keeps rising steadily [384, 385] as if no mitigation action had been taken over the last five decades. Mitigation programs encouraging nation-states to deploy renewable sources have not produced positive results on a global scale yet. Beyond being ineffective, these strategies mislead the public by suggesting that proactive actions are being taken to reduce emissions, which is far from reality.

Since global emissions keep rising almost steadily [384, 385], it has become clear that tackling the global emission problem via the UN has not been an effective approach [386]. Disregarding the historical failures incurred so far will not cause the problem to disappear. By repeating the same modus operandi, the UN turns out to be relaying a misleading message of hope to the public. While the UN keeps sending an ambiguous message to global decision-makers, it is also clogging the pipeline for other solutions, and the problem worsens.

Quantifying nation-state and substate emissions is an extremely challenging pursuit. GHG emissions are transparent, colourless, odourless, tasteless, and released remotely. For instance, the emissions to keep Western Europe warmer in the winter and cooler in the summer are released in the Northern Sea, Eastern Europe, the Middle East, and Africa [387, 388]. So, establishing territorial accountability is nearly impossible, as developed nations outsource their emissions elsewhere.

Once gas molecules reach the troposphere, remix, and react with other gases, there is no scientific method to track them back to their origins. So, emissions forensics becomes impossible due to sovereignty. Some biased agencies may still claim that certain developed countries have met their targets for lowering local emissions; however, such a claim defies logic and common sense and confuse the public. Given that global emissions keep rising and developed countries depend heavily on imported fossil fuels, claiming territorial reduction becomes meaningless.

The global value chain adds new complexity layers to quantifying, tracking provenance, and establishing emission forensics (accountability). Most manufactured products have components, with sub-parts sourced from dozens of countries. The recent shift in industrial manufacturing to developing countries (e.g., China, India, Vietnam) create extra complexities in tracing carbon accountability. Processes are not transparent, and quality data may be inexistent, low willingness from the supplier, and the pressure for lower prices. Assumptions can be easy when there is no means of verification and validation. So, the uncertainty range increases significantly, which suits most stakeholders on the producer's side.

From a global environment standpoint, it makes no difference if GHG emissions are released in Asia or Europe since the net environmental consequences are identical. Given that GHG atmospheric concentrations continue to rise steadily, proving local sustainability becomes contradictory and undermines any eventual global solution. The deployment of non-scientific models to prove territorial sustainability has been widely used by biased stakeholders, helping the global problem worsen. Claiming local sustainability is a derivative of IPCC recommendations, which helps mask global accountability from developed countries, further explored in the next section.

4.1.5 On IPCC Recommendations To Mitigate Emissions

In the absence of a qualified organisation with strong subject matter expertise in managing the global commons, power brokers tasked the United Nations (UN) to take over the responsibility for solving the global emissions problem. The Intergovernmental Panel on Climate Change (IPCC) is an organisation founded in 1988, headquartered in Geneva, and sponsored by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) [77]. IPCC has been continually releasing assessment reports, including significant causal relations of anthropological global warming, followed by recommendations aimed at decision-makers worldwide [77]. A series of instruments have been presented through the UN umbrella over the last 30 years, e.g., the Rio Earth Summit

(1992), Kyoto Protocol (1997), Paris Agreement (2015), the yearly Conference of Parties (COPs), along with the IPCC.

Financial contributions to the UN are voluntary [50, 51], where top contributors have a long history with emissions [389, 390], which opens large gaps for biases favouring the most industrialised countries. The IPCC recommendations represent the understanding of a scientific body sponsored by the UN; however, IPCC does not carry out the research themselves. Instead, they outsource research activities to third parties, creating more space for biases and risks. The IPCC provides scientific information to policymakers, which serves as the base for developing territorial climate policies. There are several loopholes with this approach.

Outsourcing may be a great solution for lowering compliance risks and costs and increasing competitiveness and resource reach. However, the outsourcer often knows inside out the tasks, or at least the expected outcome, so they still can control the major decision points and leverage the outcome from the service provider. In this case, the scope is to mitigate climate change by lowering global emissions.

IPCC released a recommendation in 2014 suggesting using natural gas instead of coal which triggered a wave of transition to natural gas [391]. A field research team in the USA used a different approach to measuring emissions, the "*bottleneck method"* [392, 393]. As an alternative to measuring the emissions at the end-use, the burning phase of fossil fuel use, all the phases were included: exploration, mining, refining, transporting, and burning fossil fuels. The results indicated that oil represented (47%) and gas pipelines(44%), which contrasted with IPCC recommendations. Conflict of interest, field expertise (or lack), and biases when conducting research involving the environment have always been a concern [394, 395, 396].

Solving the global emissions problem requires more effort than presenting reports on physical science, impacts, and high-level mitigation recommendations. The goal is to lower emissions and not produce reports. Field experience cannot be replaced by thousands of academics and bureaucrats. Since global emissions keep rising steadily [365, 385], it can be safely inferred that UN efforts so far have been inefficient and ineffective. Without a comprehensive and sound plan tackling all the root causes of emissions, there is a very low prospect for the IPCC recommendations to make a difference in the status quo.

The notion that the developed and developing economies will come together under the UN's lead on equal terms is another unrealistic expectation. There is past environmental damage caused by North America and Europe that must be taken into account. Moreover, to implement an efficient global program to lower emissions, it would be mandatory to create a global authority to enforce cross boundaries of law enforcement. However, sovereignty rights protect a nation-state against external interferences, which creates a deadlock for global consensus. This deadlock suits many stakeholders willing to remain with the status quo.

Carbon offset is a mitigation policy proposed by the Kyoto Protocol [397] targeting the removal of emissions. In theory, it is supposed to pressure organisations to find solutions to reduce their carbon footprint. It turns CO2 emissions into a commodity that can be commercialised via a regulator. When organisations cannot lower their emissions, they use carbon offsets to pay for the same amount of emission reduced elsewhere. Offsets usually support projects that in theory, are capable of reducing GHG emissions through deployment of renewable energy, carbon sequestration, methane capture, reforestation, improving energy efficiency, and more.

Carbon credits are measured in *carbon dioxide equivalent* (CO2-e) and represent permission to release emissions, a legal entitlement to commercialise this allowance with a third party through a broker. Through the carbon credit scheme, "*carbon revenue flows vertically from companies to regulators, though companies who end up with excess credits can sell them to other companies* [398, 399]. Most carbon credits are part of cap-and-trade systems, so companies can buy, sell and trade their credits. Carbon offset has become a line of business and is criticised for its inefficiency and greenwashing properties [400].

Negative emissions are promises that future activities will be capable of reducing CO_2 (CH_4) – which demotivates a solution in the present. Suppose the scenario when a true solution to reduce emissions in the present cost x and purchasing carbon credit from a third party might cost x/2. In that case, organisations are motivated to burn fossil fuel as an alternative and then claim the allowances, transferring the problem to the future. From that perspective, carbon credit could be providing a disservice to the planet. Negative emissions create a form of revenue stream for some stakeholders while providing an allowance to emit more emissions. It resonates with the "*burn now, pay later*" marketing attitude [401, 398].

It is understandable why governments, transnational corporations, and intermediaries push for a solution via the United Nations. It becomes clear why the media has been so intense in marketing the transition to renewables. However, proposed solutions have not yielded any significant results in lowering global emissions. Whereas these strategies have very low chances of prospering, global emissions keep rising in a quasi-exponential fashion [365].

As IPCC guidelines are merely informative, not a regulation, nations can set their own emissions targets, known as Nationally Determined Contributions (NDC), in alignment with their development capacities. Several problems can arise with this approach: (i) a group of countries send their ambitious emissions pledges – which in theory, satisfy the requirements, (ii) another group may partially agree and manage to pledge to ambiguous promises, while (iii) a third group ignore the recommendations since they have other priorities in the pipeline. The outcome is that emissions keep rising, and the global emissions problem is carried over indefinitely.

When regulation is specific, countries will not form a global consensus. Conversely, if regulation is vague and flexible, most countries will agree to the consensus - however, the outcome would be feeble, which leads to the present status quo. Developed nations can easily reduce their territorial emissions by outsourcing carbon-intensive activities to less developed countries. Carbon leakage undermines all efforts for an efficient global climate policy. Emissions displacement implies that a country's foreign trade contributes to reducing its domestic emissions while increasing emissions elsewhere [402]

4.2 UNDERSTANDING THE GLOBAL EMISSIONS PROBLEM

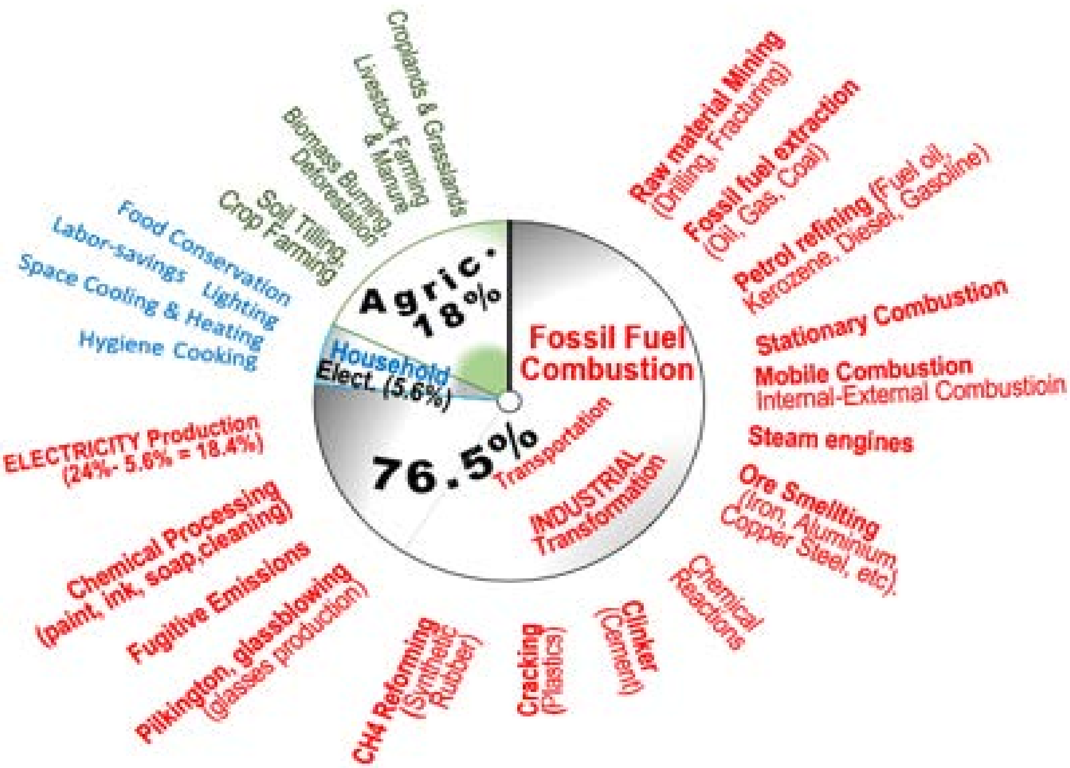
Anthropogenic GHG emissions result from wasted energy misdirected to the atmosphere without proper mitigation measures. It is a collective problem with many causes, sources, drivers and root causes. This study proposes classifying the emission problem into four lenses: causes, sources, drivers and root causes. In short, the causes refer to the processes and methods, e.g., combustion of fossil fuel, tilling of the soil, and organic waste; Emission sources refer to geographic regions, economic sectors, site facilities, static or movable sources (e.g., cars, ships); Emission drivers refer to motivational factors, constraints, conditions that impact on individuals, organisations, or governments to increase consumption – and consequently release more emissions. Lastly, the root causes are the intangible and magnified drivers that directly or indirectly force (or condition) the decision-makers to generate emissions. This section describes each of these categories in more detail.

4.2.1 The Causes of GHG Emissions

The cause of emissions refers to activities, methods, and processes that directly or not result in the release of emissions. On a physical level, the deployment of inefficient methods causes the release of emissions. A wasteful system (e.g., steam engine) may cause the loss of energy released into the atmosphere in harmful gases. On a social and collective level, emissions are caused by a series of actors working together to facilitate and encourage people to keep feverishly consuming. Most entities are fully dependent on the continuous flow of production and consumption. Individuals cause emissions by using and consuming products (or services) that have emissions associated with them. There are many layers of abstraction, and intermediaries, making it hard for consumers to perceive their indirect participation in the emission chain.

Major causes of CO_2 emissions are related to the combustion of fossil fuels (oil, coal, natural gas) for electricity production or support industrial activities (e.g., heating, smelting).

Figure 44: Causes of Emissions (processes, methods, user activity)



Methane (CH_4) gas emissions are caused by waste decomposition, enteric fermentation by ruminants, oil and gas systems, coal mining, and many industrial processes (e.g., Steam Methane Reform – SMR, pipelines for transportation). Manure handling from livestock, liming and urea in rice cultivation can release methane (CH_4) and nitrous oxide emissions (N_20). Refrigeration systems, insulating chemical materials, can cause the release of fluorinated gases (HFCs) [367].

Many industrial processes require the combustion of fossil fuels to produce heat or cause chemical reactions. Iron, steel, metals, plastics, and many other transformation processes are some. Power plants generally deploy coal, gas, or oil to heat a turbo engine to generate electricity. Steam machines, turbojets, and internal and external engines release emissions in transportation. In construction, earthmoving, construction debris, incineration, and organic waste from landfills cause the release of emissions. However, all of these examples refer to direct emissions – because they are caused by the explicit action of the users (or group) – as they can control, stop or continue at their wish.

Conversely, indirect emissions are caused by third parties, and users have no visibility or control and may not be even aware of their existence. When someone acquires any product, any object – e.g., a car - the smoke released from the combustion process is a direct emission resulting from the driver's action. However, the embodied emissions for manufacturing the car, each part and component - from mining and transforming the raw materials to assembling and shipping it – are all indirect. The users have neither control over the background processes during the manufacturing – nor after the product retirement. Rubber, tires, plastics, and debris may release emissions long after disposal. The poor methods used in mining cryptocurrencies (e.g., PoW for Bitcoin, Ethereum) are a direct cause of emissions for the miner and an indirect cause of emissions triggered by the users [403].

Every manufactured object, facility (house, building, hospital), or service (the Internet, the electricity) has embedded emissions. Raw material had to be mined, extracted, transported and transformed before production, construction or operations. Every time an individual (or organisation) acquires manufactured products, they are triggering the release of emissions to third parties. They are outsourcing the labour and transformation processes to a chain of suppliers. All the intermediaries will then be re-engaged in producing a new cycle of goods, generating more emissions to serve the next consumers.

Every product carries a package of embedded emissions – however, the processes that cause the emissions are not visible to the public. Emissions related to fossil fuels represent 82% of global emissions. Of that, around 5% refers to the daily household operations and powering devices; the other 76.5% refers to the purchase of goods and services, plus the entire infrastructure made available to society (Figure 44) [404, 352]. So, 76.5% is used in industrial transformation, transportation, construction, production of iron, steel, glasses, cement clinker, and thousands of sub-products derived from petrol (rubber, plastic, ink, medicine drugs).

The burden-shifting from the industry to the user helps to mask the magnitude of the global emission problem linked to the upstream energy sector. Targeting the householder (5.26%) helps cover the energy sector participation (76%). In the meantime, it creates an extra business space for a chain of freeloaders, such as retailers, media, eCommerce, and more [352, 404]. So, it confuses the population by allowing the misleading idea that by deploying renewables and acquiring more economical appliances, users would be truly engaged in helping solve the global emissions problem. Although a tiny contribution may exist (in the long run), the bulk of the emission problem remains unsolved. Despite implementing renewable sources, GHG global emission levels rose 18.68% over the last 30 years [405].

Understanding the causes of emissions leads to a better comprehension of the consumer's participation in global emissions. Direct emissions (~5.6%) are only a small portion visible to the consumer, compared to the bulk of emissions (~76%), which are indirectly released by the industry [352, 404]. By confusing the consumer and masking accountability for indirect emissions, the entire upper stream of the energy supply and industries are free to carry on business as usual – that has been the status quo since the Industrial Revolution.

Lastly, military applications, wars, and natural disasters also cause direct and indirect emissions. Large military corporations (hidden from view) release more GHG emissions than entire countries [406]. The trend in global ecological disasters grew from 5 to over 400 per year over the last century [19, 20]. The estimated yearly costs for global environmental catastrophes are around $1.7 trillion, which is negligible compared to other non-financial damages and intangible assets such as human lives and natural habitats. According to a global survey in 2021, over 730 economists find that the benefits of action preventively far outweigh these costs [25]. The more the planet warms up, the greater the likelihood of wildfires, firestorms, volcanic eruptions, dust storms, cyclones, tornados, landslides, and earthquakes. The wind is formed due to atmospheric pressure gradient changes – originating from the sunlight, which heats the Earth unevenly, creating warm and cool spots. As more water vapour is released, the greater the pressure gradient in some areas, more floods in some places and droughts in other regions. Thus, it can be safely inferred that society also has strong (indirect) participation in emissions from natural causes. The cause of emissions refers to activities, methods, and processes that directly or not result in the release of emissions. On a physical level, the deployment of inefficient methods causes the release of emissions. A wasteful system (e.g., steam engine) may cause the loss of energy released into the atmosphere in harmful gases. On a social and collective level, emissions are caused by a series of actors working together to facilitate and encourage people to keep feverishly consuming. Most entities are fully dependent on the continuous flow of production and consumption. Individuals cause emissions by using and consuming products (or services) that have emissions associated with them. There are many layers of abstraction, and intermediaries, making it hard for consumers to perceive their indirect participation in the emission chain.

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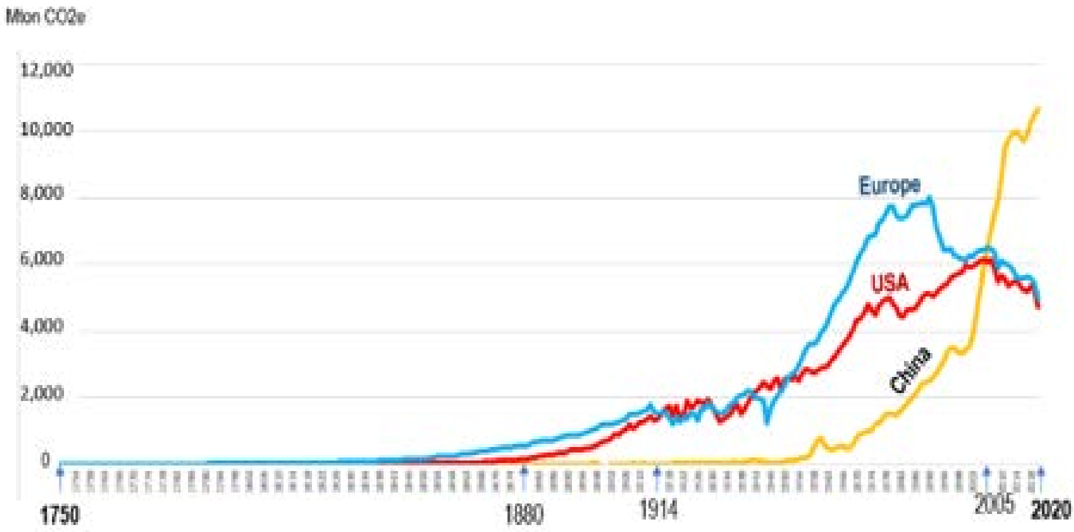


Figure 45: Carbon Dioxide yearly emissions history from 1750 to 2020: Europe, USA, China
Source data: Our World in Data

4.2.2 The Sources of GHG Emissions

Irrespective of sizes, and physical or geographical constraints, any entity that releases emissions is a source of emissions. It can be locations, economic sectors, regions, countries, facilities, or even vehicles (aeroplanes, ships, cars). Even humans can be categorised as a source since respiration causes the release of a tiny amount of carbon dioxide. Ruminants, on the other hand, such as livestock, release a significant amount of emissions. A city is a source of emissions with many causes (e.g., combustion from factories, vehicles, and construction debris). Generally, a large source of emissions refers to industrial parks, manufacturing enterprises, and facilities (e.g., a cement factory, a farm, a steel industry, a landfill).

In the 15th century, the high demand for charcoal led to massive deforestation in Europe, followed by exploitation and deforestation of colonies [407]. With the advent of the press and steam machines, Europe turned to coal to cope with the increasing demand for heating and mechanical power. Before 1880, the UK was the heaviest GHG emitter since coal was required to produce iron, railways, powering steam engines, and military applications. Figures 45 suggest that emissions have recently shifted from the USA and Europe to Asia. Around 1914, the USA's yearly emissions reached the same level as Europe. More recently, in 2005, China surpassed USA and Europe on the yearly emissions levels. In 2019, China alone was responsible for 27% of the yearly global emissions [408]. As for the accumulated emissions, since 1750, Europe, North America and Asia have been responsible for 38%, 25% and 28%, respectively, of the total global emissions. The per-capita emissions for the USA and Canada are about four times the global average.

From a global view, the fact that Europe and North America decreased local emissions over the last decade is pointless since many industrial processes have been migrated to Asian countries. This conclusion becomes transparent when analysing the historic emission curve profiles (Figure 46). It becomes highly debatable and counter-productive when a single country announces their ability to reduce local emissions. If the global levels have been continuously rising, any claim for lowering local emissions is doubtful. So far, these claims have a high political pitch and insufficient scientific evidence. The fact that the Middle Eastern countries and China became the most intensive GHG emitters on Earth becomes irrelevant – since they are just responding to the global demand, where Europe and North America remain the leading beneficiaries. . Figure 47 shows what countries and regions have mostly contributed to the release of emissions over the past two centuries [409, 360, 410].

In 2021, a group of eight countries in Europe and North America (USA, Canada, UK, Germany, France, Italy, Spain, Netherlands), holding 9% of the global population, owned 62.1% of the global market value for all companies listed in the Forbes Global 2000 list [411]. This implies that despiting part of the emission sources has been relocated to Asia over the last few decades, and the number of beneficiaries of emissions remains concentrated in Europe and North America. In other words, the recent shifting of emission sources from Europe-North America to Asia did not contribute to lower global emissions – and created an additional roadblock to combat the problem. Since Asia is rapidly increasing their emission levels, it gives European and North-American institutions peace of mind to carry on business as usual.

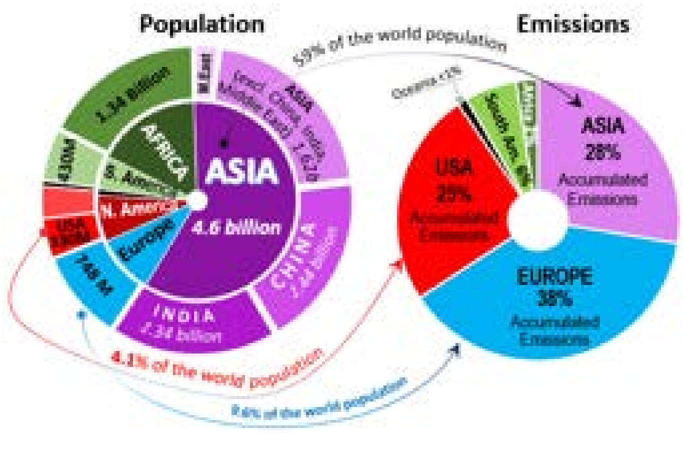


Figure 46: Accumulated CO2 Emissions from 1750 to 2020, Europe, North America, and Asia - Source: Our World In Data

Over 7,500 large scale CO2 emission sources facilities (above 0.1 metric tons of C02-equivalent) had been identified worldwide [412, 413, 414, 415]. Four main geographic clusters of

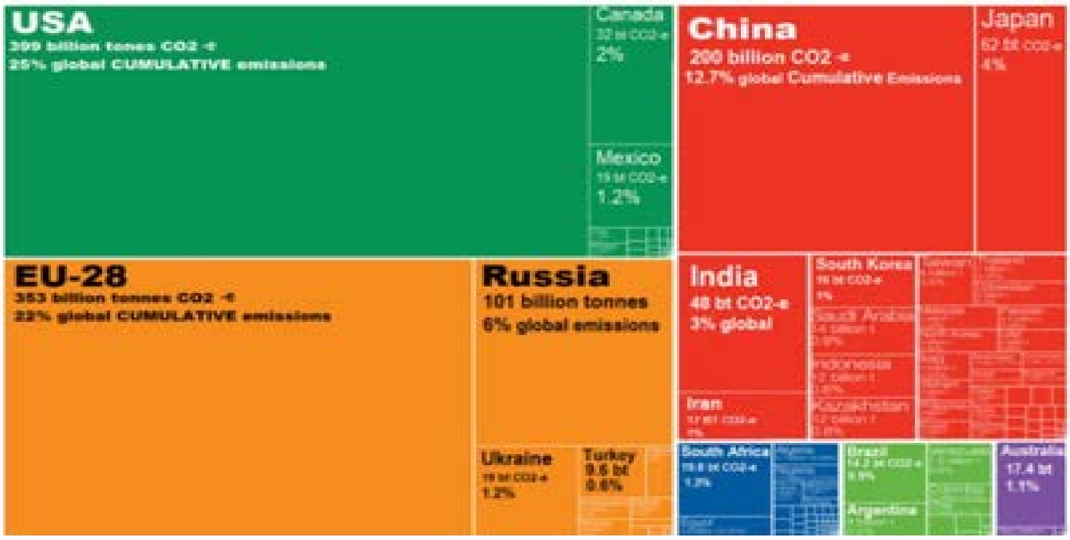


Figure 47: Cumulative Emissions per country, from 1750 to 2017 - Source: Our World in Data

emissions were observed: North America, Northwest Europe, Southeast Asia (eastern coast) and Southern Asia (Indian sub-continent). The emissions trend has been steady over four decades [384, 385]. Although Covid-19 slightly impacted the trend, the rebound came timely [336, 405]. GHG global emissions keep rising, global warming [416]. Here are some highlights of major emission sources:

- In 2020, China was responsible for 28.8% of the global emissions, with per capita emissions of 7.1 tons CO2-e and GDP per capita of $10.954 yearly. The global average per-capita emission (2020) was 4.6 tons of CO2-e yearly [417].
- In the same year (2020), the USA was responsible for 15.04% of the global emissions, with per-capita emissions of 16.1 MtCO2-e.
- Heavy industry is responsible for 22% of global CO2 emissions. Of that, 10% is used for combustion to generate industrial heat [390, 418].
- Steel and cement account for approximately 14% of global CO_2 emissions [419, 420].
- Building and construction constitute around 38% of the global emissions, including steel, aluminium, cement, and glass [421].
- The energy sector (electricity, heat, transportation) is responsible for over 73% of the global GHG emissions [422].
- 82 % of the global (total) emissions in 2018 were associated with fossil CO2 emissions and 18 % by land-use change [351, 419];
- Iron and steel production are highly energy-intensive industrial sectors. These products accounted for 22% of the global emissions in 2019 [420].

Sources can change location over time, change, adapt, and mix with other sources. Global emissions are a global problem and should not be restricted to locations or sources. Although the source is located on continent A, the triggers can be in continents B and C. Sources' geolocation has continually changed over time. It highly depends on commercial interests, national strategies, and international affairs. Identifying the sources has very little significance in solving the global emission problem. What matters most is who owns and controls the sources or has the power to stop, mitigate, or continue the emissions. Figure 48 shows the main sources of GHG emissions by industries.

Unless a country is self-isolated from the global value chain, there is no reliable and scientific method to quantify the exact participation of each nation. There are plenty of approaches for calculating emissions based on frameworks started by the Kyoto protocol. However, they are heavily based on assumptions, and their contribution to solving climate change is debatable. Carbon offsetting solutions became a line of business and have been criticised for serving as greenwashing tools [400]. Therefore, claiming the success of a local emission solution has low significance when global emissions keep rising.

Finding the source of emissions helps locate the problem and brings some tangibility; however, it has a limited reach since there are always drivers leading the source to release emissions. For instance, the heavy industry sector (construction, metal production, mining) is an intense emission source. Metals, cement, and chemicals are the top three emitting industries that are the most difficult to decarbonise [418]. Nevertheless, the entire public infrastructure, i.e., hospitals, schools, and roads, fully depends on heavy industry. So, the existence of the public infrastructure is an outcome of the emissions released by the heavy industry. The sources are only part of a big picture, with hundreds of stakeholders.

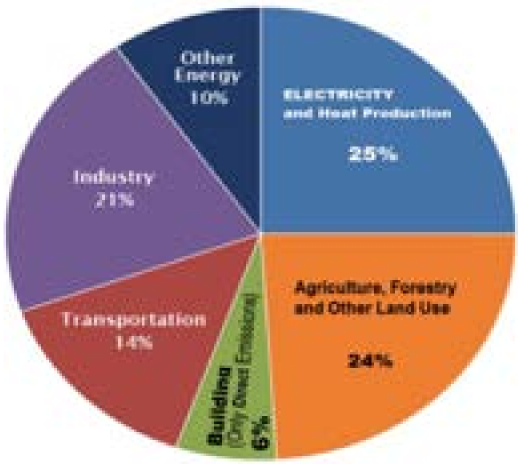


Figure 48: Global Emission Sources (per

Quantifying emissions by economic sector is challenging and debatable. Although it can be estimated by compiling inputs from different sectors, accuracy is highly debatable. There are no tools to disaggregate the emissions and establish provenance. There is no entity measuring emissions by sector because all the economic sectors are fully interconnected, with no clear boundaries. E.g., The education sector depends on the government that relies on the financial system, who needs the industries, and so forth. All calculations are based on estimations, factors, and assumptions, creating huge uncertainties.

Nevertheless, several studies on GHG emission sources present breaking down per gas type or others per industrial sector [351, 423, 424, 425, 426, 427]. The IPCC reports for each economic sector can be relevant referential [428, 429, 430, 431, 432]. A comprehensive data library for global, regional and national greenhouse emissions by sector between 1970 and 2018 has been compiled by [433]. The inventory classifies the emissions according to gas types, CO_2, CH_4, N_2O, and fluorinated gases (F-gases: HFCs, PFCs, SF_6, NF_3). Nevertheless, the authors highlight uncertainties in the scientific methods for estimating GHG emissions [433].

Any institution that, directly or not, depends on energy, physical infrastructure, transportation, communication, or manufacturing goods, is automatically linked to the emissions' flow – although they may not be the ones releasing the emissions. It is rather challenging to identify a single institution (business, public, social, government, community) that does not require daily public infrastructure, telephone, electricity, fuel, consumer goods, or building facilities to survive.

Advancements in technology (the Internet, digital communication, software applications) enabled the creation of a worldwide network of institutions. Millions of institutions are now interconnected, forming a massive global chain. They are true drivers of emissions, which are further explored in the next sub-section.

4.2.3 THE DRIVERS OF GHG EMISSIONS

The drivers refer to the underlying motivation, stimulation, reasons, beneficiaries, or enablers that lead to GHG emissions. The myth that "*progress is inevitable*" [7] has been ingrained in society over centuries, rooted in culture, beliefs, and convictions. The idea of consumers and producers took shape in the USA around World War I [434]. Since then, millions of intermediary organisations have emerged to facilitate and motivate the increase in production and consumption.

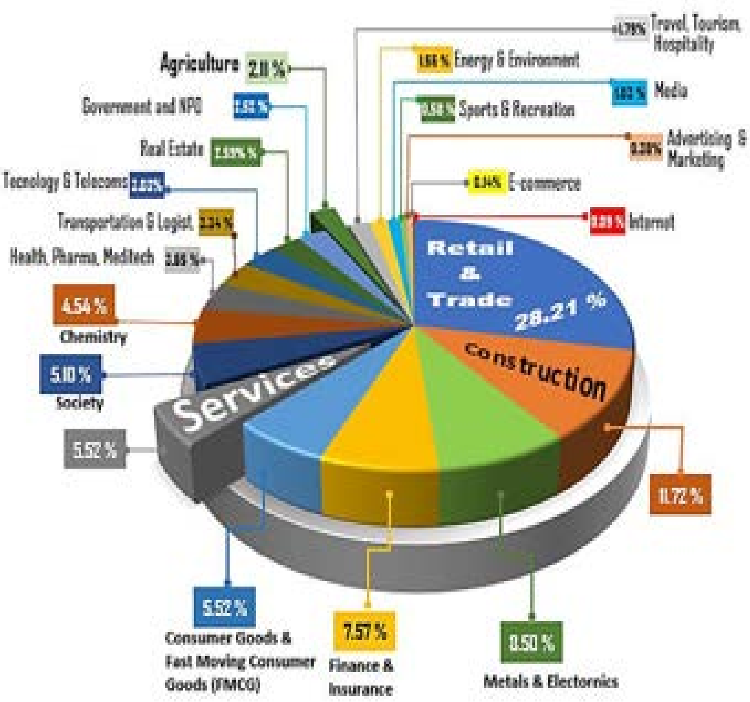


Figure 49: 214 million companies worldwide distributed by sector (%)

The division of labour suggested that specialised workers performing specific tasks would increase productivity, drastically reduce the cost of goods, and reduce training. Instead of learning every aspect of the production, workers needed to learn one portion of it. On the other hand, coordinating all these different tasks requires greater management. Due to the Industrial Revolution, the proliferation of multinational corporations, and advances in logistics, and technology, it has become increasingly hard to identify truly national products.

There were roughly 214 million companies worldwide in 2020, and their distribution per industry is shown in (Figures 49 e 50) [22]. Each of these organisations has clear objectives, commitments and targets to achieve. Even a not-for-profit organisation still rely on profits from third parties to survive. The number of intermediary organisations is far greater than the producers. They focus on stimulating or facilitating acquisitions. Although they do not release the emissions themselves, they encourage

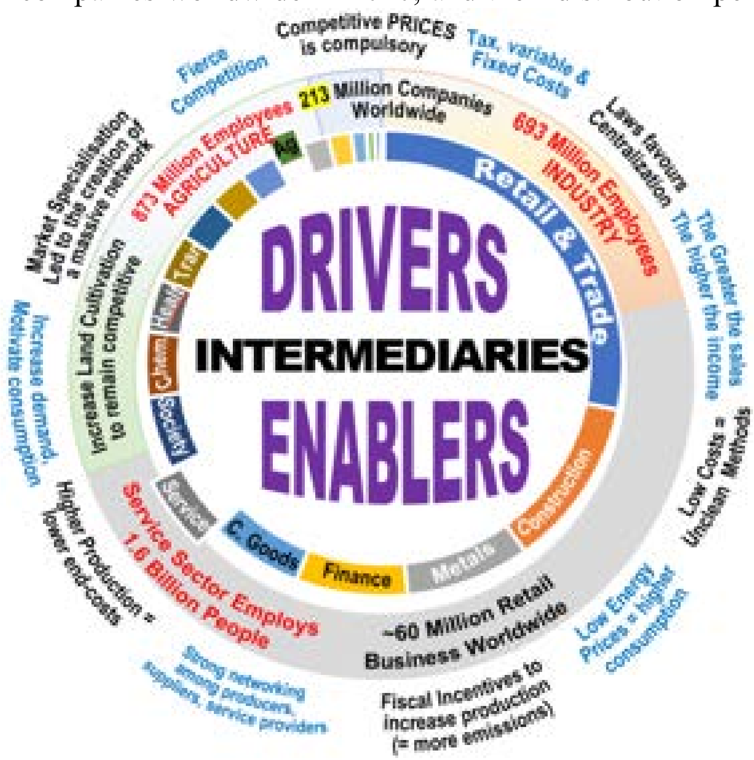


Figure 50: 75 million companies that are emission enablers

higher consumption and become freeloaders on the global emission problem. Since they increase sales, they benefit from emissions; however, they do not take accountability for the portion of emissions released resultant from their activities. Thus, they are equally responsible for emissions since they drive, facilitate, or encourage consumers to increase acquisitions.

Producers count on retailers, media, advertisers, and intermediaries to commercialise their products. Retail and traders represent about 28% of the total companies worldwide (over 60 million organisations) [435]. The retailers facilitate consumers' acquisitions, and their ultimate goal is to increase yearly sales. They count on ads, tools, media and a chain of service suppliers to increase sales.

The financial sector controls the flow of income and expenditure within and outside the community. The greater the long-term engagement between producers, intermediaries, and consumers, the better for business. Thus, producers, retailers, the service sector, and logistics became closely interconnected through the financial sector. The entire ecosystem only functions together and cannot survive independently. The public sector is no different since community infrastructure, hospitals, schools, and roads rely on the industries for taxes, social security, and fees. Thus, the financial sector is a key enabler for stimulating business – and global emissions.

Newer appliances are systematically offered to the public daily, with no reference to the embedded emissions. Instead, energy efficiency labels were introduced a few decades ago. It brings an initial positive face value by reducing daily consumption; however, it masks a much bigger problem: by contributing to the 'greenwashing' acquisition process. As it is, the labelling is far more helping the retailers, producers, intermediaries and governments to keep their benefits rather than helping the planet to reduce emissions - because it hides the embedded emissions from the upper stream energy sector (fossil fuel, electricity, heavy metals, miners, industry).

The labelling system backfires by confusing the public – since it creates a false expectation for the buyer as a contribution to the environment. As mentioned previously, GHG concentration levels rose 18.68% over the last 30 years [436], when the energy efficiency labelling system became popular. Since the labelling system only focuses on the energy consumed during operations [352], it tackles only a smart part of the problem, the direct emissions (5.5%) and ignores the indirect emissions (76.5%) [351, 352]. Thus, the labelling system has become an emission driver rather than a mitigation strategy to lower emissions.

Drivers, or enablers, can also be related to socio-economic factors, like population, *Gross Domestic Product* (GDP), and *Human Development Index* (HDI). They all have been persistently growing over the last 50 years, and so have emissions:

- The global population raised from 3.70 billion in 1970 to 7.79 billion in 2020 [437];
- The global GDP increased from $2.98 trillion to 84.74 trillion in the same period [438];
- The global average HDI raised from 0.601 in 1990 to 0.737 in 2020 [439];
- The global GHG emission levels increased from 14,897 (in 1970) to 34,807 million metric tons CO2-e (in 2020) [440];

The correlation between economic growth (GDP), education (HDI), population growth, and GHG emissions levels have been well established in the literature [441, 442, 443, 444]. The higher the trade levels, the higher the global emissions [445, 446]. Unless scope 3 of the Greenhouse Gas Protocol [447] is rigorously taken into account, claiming the possibility of decoupling GDP and HDI from territorial emissions by simulating data models based on assumptions is highly questionable. Besides, GHG emissions keep rising steadily. On 14 Feb 2022, emissions reached 421.59 parts per million (ppm), the highest level ever recorded in history by the Mauna Loa observatory, based in Hawaii, USA [384].

Since carbon-intensive activities have gradually been outsourced to developing countries, it is naturally expected a decrease in emissions for the most developed nations. As mentioned in section 2b), a group of eight countries (USA, Canada, UK, Germany, France, Italy, Spain, Netherlands), holding 9% of the global population (~713 million), was responsible for 43% of the global GDP, and 23.5% of the global emissions (in 2021). This selective group of nations own 62.1% of the global market value for all companies listed in the Forbes Global 2000 list (for that same year). Most of these countries have been claiming they have reduced territorial emissions while growing their GDP [448].

There are several classes of emission drivers, and tangibility may vary. Some may include socioeconomic factors, pure marketing tools, technology, law & regulation, mode shift, human behaviours, socialisation, global value chain (imports vs exports), and many more. Laws have been created to protect the rights of service providers, producers, consumers, intellectual property rights (patents) and many other aspects. Despite all the attempts, the laws have been a major driver of emissions.

The high educational segment is a classic example of an emission driver. When demand for a specific skill (or tool) arises from the industries (or government), educational institutions promptly create a product to fulfil the needs. Schools create customised products (disciplines) and make their services available to the public, similar to any other business. Disciplines such as IoT, Cloud Computing, and Machine Learning are flagships in many institutions. In the public view, schools provide a service to society by providing training. From an environmental perspective, schools merely create a service for mass consumption in exchange for rewards. Once the training is delivered, the school have no control over what happens to the student – nor the consequence to the environment.

Later, graduate trainees will use tools and techniques to multiply production, speed processes, optimise costs and performance – and drive the emission levels up. Given that it takes a very long time until the problem is detected by society, the schools keep benefitting from emissions without being accountable for their participation in the process. Like most intermediary organisations, e.g., service providers and retailers, the schools are not generating the emission themselves. Nevertheless, they are assisting other stakeholders in releasing emissions and benefitting from it.

The high-tech industry is another illustration of an emission driver. It covers various organisations, e.g., electronics, semiconductors, computers, communication equipment, software, robotics, and many more. Take the software industry, for instance - writing and testing codes do not involve burning fossil fossils or emission generation. However, the software is always present in every stage of an industrialised product - from prospecting sales through logistics and manufacturing to packaging and delivery. Thus, the software industry is a key participant in the emission flow. It can be safely inferred that if not for the software industry, most existing landfills would be empty. There would be only a fraction of production, sales and delivery – and much lower emissions. The same concept can be extended to computers, electronics, semiconductors, or media.

GHG emission levels are strongly correlated with the production and consumption of goods [449, 346, 347, 348, 349, 350, 441]. The higher the production, the higher the mining, exploration activities, importation, exportation, and transportation. Consumption, on the other hand, is highly correlated with employment and per-capita income. There was an increase of 42% in employment over the last 30 years - and CO2-e concentration levels raised 18% in the same period [365]. The increase in employment automatically leads to improved economic performance and purchasing power. Without credible mechanisms and policies to restrain emissions, employment rates become another hidden driver behind the emissions.

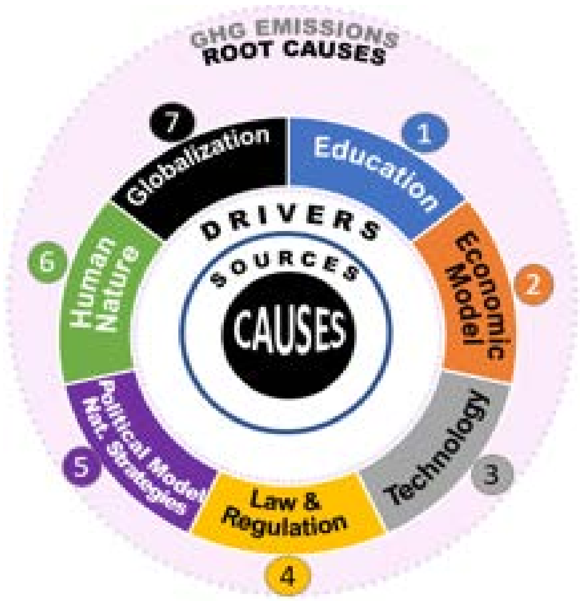


Figure 51: The Seven Root causes of emissions

In 2021 there were 1.6 billion people in the services sector, also known as the tertiary sector. Then, 693 million were in the industry and 873 million in the agriculture sectors [450]. The tertiary sector provides services (or *intangible goods)* to other businesses or final consumers instead of end products. It includes transportation, commercialisation, distribution, delivery, and support for goods and services in telecoms, IT, mass media, consulting, public health, hospitality, gambling, financial services (banking, insurance), education, legal services, and many other domains.

The service sector is not characterised by the emissions it generates; however, it is part of the emissions loop and supports every other sector. The service sector workforce represents roughly 50% of the total employees worldwide, influencing every aspect of society. With tertiarisation and globalisation, and millions of containers cruising seas daily, tracking emissions provenance at the component level becomes highly infeasible [56, 57]. Like a freeloader, the service sector has enjoyed the benefits obtained through organisations that deploy unclean methods without sharing the accountability for the emissions. The bulk of the service sector would not exist without if not by the industry and agriculture sectors. So, clearly, the service sector is a major driver of emissions

4.2.4 WHO ARE THE ACTORS IN THE EMISSIONS' FLOW?

Emissions are triggered by a series of factors rooted in individual, corporative, and governmental needs. Whereas the individual's basic needs can be restricted to food, shelter, and clothes, humans desire comfortable lifestyles, luxury goods, socialisation, entertainment, and many more. Both needs and desires can be manipulated, making the line between essential and inessential blurry, moveable, or undetectable. That is where education would play a significant role in protecting the individual against over-consumption and the environment against pollution.

Instead, intermediaries explore the boundary between needs and desires to increase consumption rates and obtain financial advantages. A few points to be taken into consideration:

- Emissions have been released in proportion to the volume of goods and services produced, commercialised, and disposed of;
- The government is an interested party in the increase of production and demand and systematically develops strategic planning to meet those needs;
- The introduction of subsidies and other incentives motivate the local industry to increase production and trade;
- Power brokers are elected for a defined period with the main task of ensuring economic growth - only then they can provide a better lifestyle for their citizens;
- The population from developed countries has already become accustomed to the intensive carbon lifestyle, taking it for a grant and making it harder for new approaches
- Consumers are vulnerable to media, marketing, advertising, and short-term advantages - and intermediary companies have learned how to explore this gap opportunity;
- Technology is widely used in support of the industry to increase productivity and lower costs - as well as inducing the user towards a higher consumption state;

Thus, it is possible to determine the main participants in the global emission flow, depicted in Figure 52. There are a few types of corporations; some are producers, while others are intermediaries. Then, there are the individuals and government who orchestrate the flow of information between producers and consumers.

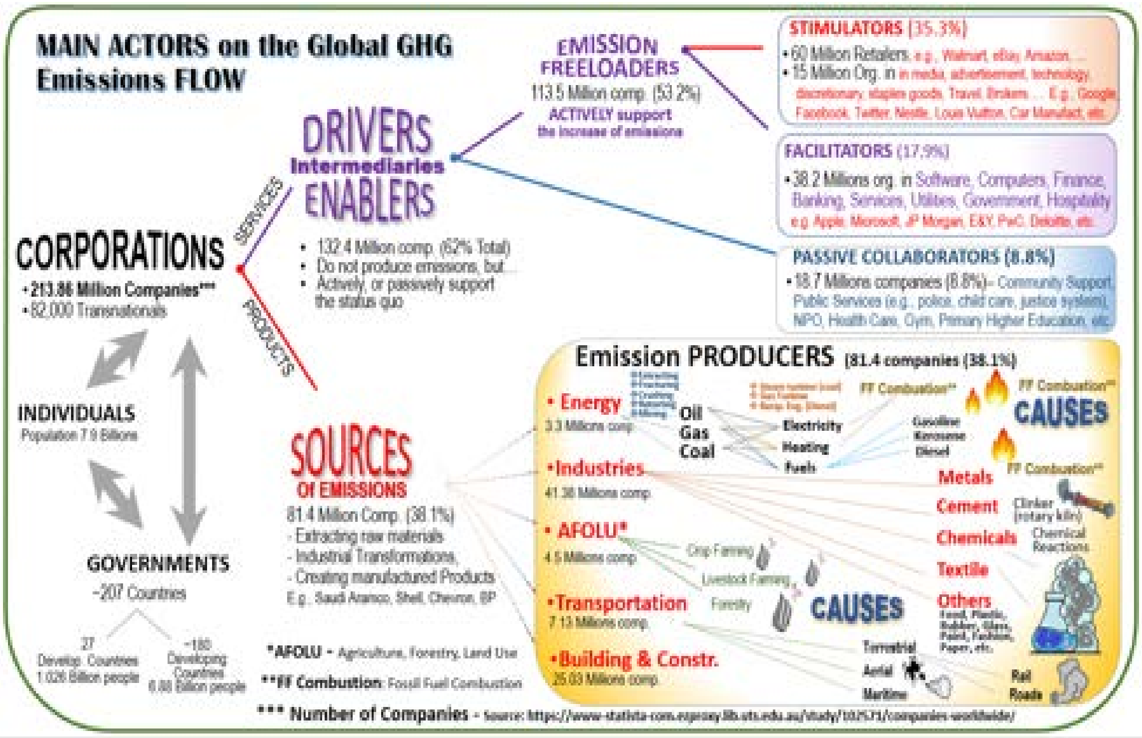
From an emission standpoint, corporations can be classified into sources and drivers of emissions. The sources of emissions are linked to institutions that extract minerals, petroleum, and natural gas (primary sector), to a lesser degree to manufacturers that produce finished goods (secondary sector), and to an even lesser degree to the service sector. However, the flow of emissions is triggered from the opposite direction, from the service (tertiary) sector.

Of an estimated total of 213 million companies worldwide [435], 81.4 million (or 38%) can be classified as producers (of fossil fuels, electricity, or finished goods). Although the number of producers is very expressive, there are a few caveats. According to the '*Carbon Majors*' [451] database:

- A group of 100 corporations in the fossil fuel industry are accountable for 71% of the industrial GHG releases.
- 59% are state-owned organisations, and 9% are from the private sector.
- 32% of the cumulative GHG emissions are from publicly listed companies.
- 25 corporate and state producers account for over half of the total emissions since 1988 [452].
- Fossil fuel organisations have released more pollution over the last 28 years than in the 237 years before 1988 [452].
- 52% of cumulative global emissions are traceable to 100 fossil fuel producers – counting from the start of the industrial revolution (middle 18th century) [452].

Price and reliability are bottom-line factors for the energy sector since it impacts the costs of every other product and service on Earth. A mosaic of constraints envelops the energy sector, including environmental, socio-political, technical, legal, and economic factors (laisses-faire, monopoly, oil cartels). Major oil and gas producers include the USA, Saudi Arabia, Russia, Canada, and China. Energy security and the environmental impact are

Figure 52: Overview of the global GHG emissions flow - sources, drivers causes, and main actors



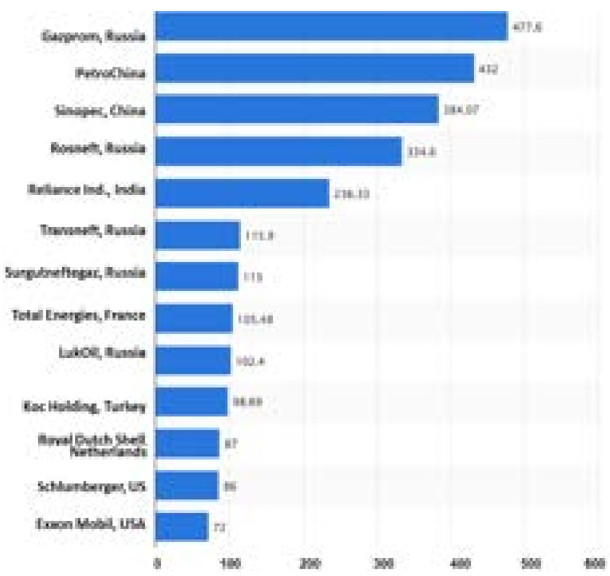
conflicting dilemmas. Figure 53 shows leading oil and gas companies ranked by the number of employees [453]. By market cap, some of the largest oil and gas companies are Saudi Aramco, Exon Mobil, Chevron, Shell and BP [411].

Producers of emissions also include large corporations in consumer staples (e.g., P&G, Coca-Cola, Nestle, AbInBev), consumer discretionary or non-essential consumer goods (e.g., Apple, Microsoft, Volkswagen, Boeing, Louis Vuitton), basic materials (BHP, Lynde), chemicals, building and construction, and many others.

The tertiary sector (or service sector) holds all the intermediary companies that provide support to the business by stimulating, facilitating, or passively supporting the increase of sales, which translates to emissions. The intermediaries link producers and end-consumers. The higher the development of a nation, the stronger the service sector. Although they do not release large quantities of emissions, they are a key actor in the emission flow since they promote or assist other stakeholders in increasing sales. Intermediaries are key emission drivers and can be classified into stimulators, facilitators, and passive supporters.

Stimulators of emissions refer to a broad class of companies that generate business by triggering more acquisitions and consumption. There are an estimated 75 million organisations under this category. Of that, 60 million are retailers, and the remainder is in services, media, advertising, hospitality, brokers, and dozens more. Large corporations in the retail business include Amazon, Walmart, and eBay, while in digital advertising, including Google, Facebook, Twitter – and thousands more.

Figure 53: Leading Oil and Gas Companies



The software industry can be either a stimulator or facilitator, depending on the functionality involved. The software relies on multimedia devices (smartphones, tablets, desktops) which depend on the networking infrastructure. Thus, all-digital technology suppliers, vendors, utilities, and content providers became close associates with emission stimulators. They all complement each other towards engaging consumers to increase consumption, and they cannot survive on their own.

Emission facilitators differ from stimulators since they do not motivate acquisitions - they provide the infrastructure and support. Telecoms, banking, utilities, brokers, and real estate are classic examples of facilitators. An estimated 38.2 million companies in the financial, real estate, services (tertiary sector), and utilities. Without the financial system infrastructure, there would not exist business, no commercialisation of products, and no emissions. Like the stimulators, emission facilitators do not release emissions but actively support the increase of production and, therefore, emissions.

Lastly, the passive collaborators include all the institutions that peacefully accept and support the continuation of the status quo. They also benefit from emissions, however, not financially. Community services, government infrastructure (e.g., police, justice), childcare, non-profit organisations, and primary schools are all emission neutral (for the most part). However, they still have to obtain funds from somewhere (e.g., government, donators) – and their supporters are either producers, stimulators, or facilitators, of emissions. Producers, stimulators and facilitators profit from higher emission rates since the more they produce or commercialise products, the higher their income. Pass supporters collect the benefits without getting involved with emissions – becoming free-riders of emissions.

4.2.5 The Forensics of GHG Global Emissions

Once emissions have been released into the atmosphere, dispersed, mixed and reacted with other gases, they cannot be traced back to their origins. Establishing accountability for emissions requires scientific methods for measuring, monitoring, and reporting the emissions at the sources.

Problems arise when thousands of emission producers and millions of emission drivers and facilitators work together, complementing each other, and no entity takes responsibility for mitigating the problem. Every entity (individual or enterprise) has a degree of participation in the global emission flow. Any organisation that conducts business (or relies on funds from someone else who does), e.g., uses electricity, fuel, fertilisers, transportation, or any public infrastructure – is automatically benefiting from emissions. The higher the development of the population (HDI, GDP), the higher the consumerism, and thus, emissions [417]. Except for a few disadvantaged groups (indigenous, poor and remote communities, or small farmers), the total population benefits from emissions. Their participation varies with their living standards and role in society.

Upstream energy suppliers and manufacturers often deploy polluted methods to lower production costs, improve competitiveness, and maximise gains. Governments use many strategies to motivate corporations to lower costs to increase exports. The intermediaries, stimulators and facilitators also play a crucial role in boosting consumption and acquisition, triggering more emissions. In power systems, the flow of emissions is initiated by the consumers rather than the producers [454]. The combustion of fossil fuel is the last step required to attend to the demand from the consumers.

The consumer triggers the release of emissions on every product acquisition. Consumers are influenced by advertising and the level of environmental education. The lower the education towards the environment, the greater the thirst for consumption, and the higher the vulnerability to advertisers, media, and propaganda. As mentioned in the previous section, some of the largest institutions (e.g., Google, Facebook, Twitter) rely on advertising as their main source of income. The service offered is to maximise sales and increase wasteful consumption, which stimulates more emissions.

Measuring and reporting the release of emissions requires procedures, clear regulations, and verification authority. Transparency and trust at an international level require a bi-directional relationship beyond state borders. However, this is unrealistic in the present for several reasons. Firstly, it is highly unlikely that competitive nations would agree to disclose their real participation in global emissions because of national security reasons and sovereignty. Secondly, developed countries house the large majority of transnational corporations – and once information on emissions is disclosed, it would bring high risks with high impacts for their corporations. Thirdly, developing countries do not have the infrastructure to implement strict procedures. Fourth, the higher the ambiguities on global emissions, the better for most of the industrialised.

The developed nations could achieve it - however, that would negatively impact their existing business and attract high risks for their economies, opening gaps for competitors. Thus, as a strategy, transnational corporations from developed nations have been systematically outsourcing emission-intensive activities to developing nations. That created new layers of complexity since the burden for solving the global emission problem is now shared with several developing countries (mostly Asia countries).

Another major roadblock to measuring, reporting and ensuring global compliance for reducing emissions emerged when corporations from North America and Europe shifted part of their operations to Asia. This gradually happened over the last two decades. Under this new configuration, Asian countries have a very large population so they can accommodate far more emissions per capita. That strategy distributed the risks and accountability across many countries – without solving the problem. On the contrary, emissions keep rising, and the complexities are greater than before.

A growing number of high-tech and consumer goods corporations have committed to 100% renewable power under the RE100 initiative [455]. On the other hand, a recent study with 25 top corporations exaggerates, misreports, and fails to meet their progress [456]. Carbon credits and carbon offsetting (carbon marketing) represent the right of companies to emit GHG emissions and have been criticised for misreporting and serving as greenwashing tools [457, 458, 459].

Thus, it can be concluded that emission forensics in the sense of traceability, transparency, and provenance (origin) is extremely unlikely to be established on a global scale and under the current circumstances. Accordingly, the notions of sustainability and net-zero carbon are fully compromised until a global consensus establishes clear methods to manage the global commons and allow independent verification. As long as global emissions keep rising, and without proven scientific methods, planning, and clear protocols, global sustainability and net-zero transition are terms confined to the marketing and commercial realms.

4.3 ROOT CAUSES ANALYSES OF GHG EMISSIONS

All causal problems arise from their root causes. A thorough understanding of the underlying structure, the symptoms, the effects, the chronology of the events, actors, surrounding environment, triggers, conditionals, and every other aspect becomes relevant when finding a solution for an unsolved problem.

Global warming and climate change are well-established phenomena rooted in anthropogenic GHG emissions. On the other hand, the global emissions dilemma is still largely miscomprehended by educators, influencers, decision-makers and the entire public.

Until people realise the real root causes of emissions, the problem remains unsolved - which is the exact representation of the status quo. Most of the attempts so far have been contributing to delaying, postponing the solution – and in the meantime, providing false hope to the public. The GHG emissions levels (including CO_2, N_2O, CH_4, and SF_6) have risen steadily for the last five decades [365, 362, 363, 364]. Climate change is real and measurable [19, 20], leaving no margin for misunderstandings or denials.

Emission root causes refer to the higher abstraction layer leading individuals and organisations to deploy unclean methods that release GHG emissions. The root causes deal with the foundational problems, values, constraints, conditions, or underlying rules forcing (or motivating) stakeholders to make decisions that favour only short-term goals. Root causes are hardly noticeable by the public and may have emerged spontaneously over centuries.

For millenniums, the lust for power, wealth, affluence, and prosperity motivated people and nations to conquest new territories. Driven by God, gold, or glory, conquerors and kings decimated civilisations to access resources and increase territory and power. Today, there are 214 million companies worldwide driven by similar drivers. They either produce goods or provide services - and all want to conquest benefits in exchange for their products. Irrespective of their line of business, there will always be some entity in upstream energy extracting raw materials, burning fossil fuels, or devastating the land. So each of these 214 million can conduct their business.

An intense exercise, assisted by a series of techniques, has been conducted to identify the root causes of global emissions, including mind map exercises, brainstorming, the Ishikawa Diagram, and the Five Whys method. Appendix I shows the Ishikawa diagram. This section describes and describes the seven root causes of global GHG emissions.

4.3.1 EDUCATION

Parents, friends, public education, media, and the surrounding ecosystem pass educational values to children. Formal and information education both contribute to the formation of the individual. The parenting role in education has been largely outsourced to the government, which then subcontracted it to the education industry. The schooling function has been exploited financially, similar to any other business (for the most part).

Any entity that, directly or not, stimulates or facilitates the increase in acquisitions or energy consumption is necessarily contributing to rising emissions levels. The same applies to regulation or legislation that creates barriers or adds constraints undermining the shifting toward a low carbon culture is also driving and supporting the continuance of the emission problem. Emission drivers can be embedded in the training, services, technology, or applications that offer benefits to attract consumers. The user propensity towards the short-term benefits blocks the big picture, so users fail to notice what is at stake and the long-term effects on the environment.

Primary education prepares and influences young students for a lifetime. When primary education fails to raise students' environmental awareness, it contributes to the formation of careless consumers. In primary education, young people are exposed to the 'prosperity' mindset, where they are tailored to become active consumers. Students are moulded by a system that creates the consumption citizens for tomorrow. By the age of 10, students may have already built the notion that higher income leads to high power - the more, the larger they have, the higher their rank in society.

A good primary education guide pupils to become useful to society and, in the meantime, respect the environment and the rights of future generations. Conversely, the worst-case scenario is developing a high carbon society that prioritises institutional needs to the detriment of the environment. In that case, by 15, young students would have unlocked their illimited thirst for acquisitions, which would become their motivation for life. The latter reflects the high-carbon culture that humans have been locked-up, leaving no room for different choices and no space for growth as individuals.

A survey in the USA including 1,500 educators has found that most children spend less than two hours of an academic year studying climate change in middle and high school (year 7 to year 12) [460]. Moreover, much of what was taught was either unclear or incorrect [461]. According to an ATWD report in Australia, about 66% of educators do not use scientific evidence to teach their pupils - they were misinformed and lacked education [462, 463].

The HDI measures the years of schooling, the standard of living and life expectancy – however, in the absence of an education pro-environment, the HDI (and GDP) becomes a reliable tool for measuring the ability of a nation to deplete the planet. A high HDI leads to an increase in GDP and consequently to higher consumption and emission levels. More recently, the happiness index was introduced. As expected, the happy nations are the same, with high HDI and GDP – and the highest emission levels per capita.

The high education sector reaches further by providing tools and technologies so the industry can produce faster at the lowest cost. Polluting methods are always less costly (in the short run). A higher educational institution's reputation is measured by its ability to produce research that the industry can commercialise. With time, they have become known for their ability to incubate new institutions and accelerate the entrance of new products into the market. Many of the large corporations in technology have developed from university start-up hubs. None of these institutions is known for contributing to protecting the environment.

The higher education sector is expected to provide solutions to the GHG emissions problem, a beacon light for innovation. Instead, for the most part, it became a lighthouse for novelties that harms the environment. It is enveloped by an economic model that favours higher productivity and faces a conflict of interest between society, government and industry. It relies on funds that come either from corporations or the government. Since government revenues are tethered to the industries, the higher education sector has become fully dependent on the continuous flow of consumption.

Education became a major root cause for emissions since it educates pupils to become intense consumers, with little regard for the environmental consequences. Lowering GHG emissions inevitably requires a radical shift in the educational model. While the educational sector remains linked to the corporative interest, there is no chance of mitigating or reversing climate change. Poor education leads to poor laws, regulations, and leaders – which explains the locked-up situation faced by the planet.

4.3.2 ECONOMIC MODEL

The Industrial Revolution led to a global ecosystem where millions of organisations work together, complementing each other to increase productivity at the lowest cost. The unrestricted increase in production and consumption feeds the nation-state requirements (funds) for maintaining the public infrastructure. It encourages mass production and the deployment of low costs transformation methods as the recipe to lower costs. However, more production implies more consumption, waste and consequently more emissions. The higher the production and demand rates, the better for the government – as it can redistribute benefits to society in infrastructure, health, public education, and other social affairs. The offshoot is the long-term effects on the environment to satisfy local stakeholders.

Free-market economics is the ideological notion where agents independently seek their own gain and produce the best overall result for society, like a self-regulating machine. Adam Smith assumed and believed humans ultimately promoted public interest through their everyday economic choices [66]. Today, most of the government's income (around 95%) comes from individual income tax, social security, and corporate income tax [464]. These resources are fully dependent on economic performance, implying that more jobs lead to more production and potentially to more taxes from the sales of goods and services. Conversely, low economic performance means high risks, no jobs, low income, and instability. So, it becomes trivial that the economic model is self-destructive and uncontrollable since it does not take accountability for the damages it creates in the long run.

The current economic model has always prioritised short-term results, lowering costs by scaling production and reducing costs on processes and methods. It prioritises prices, leaving no room for environmental concerns. It solves an immediate governance problem; however, in the exchange, it creates a long-term dilemma much harder to be solved, becoming a root cause of the global emissions problem. The existing strategies, such as carbon offset, carbon market schemes, and renewable energies, have been proven ineffective and helping the global emission problem worsen [457, 458, 459]. Unless consumers raise awareness and learn how to make educated choices, forcing vendors and power brokers to change laws and take accountability for the environmental costs, there is no hope of changing the status quo.

4.3.3 TECHNOLOGY

Technology refers to applications, techniques, skills, methods, or processes embedded in machines, appliances, objects, and systems, intended for organisations or individuals. Organisations deploy technology to optimise, increase performance, and maximise opportunities at any stage of the production or commercialisation processes. Individuals use technology to save time, communication, research, comfort, entertainment, and many other purposes.

As reminded by Kranzberg [465] in the first law of technology, *"Technology is neither good nor bad; nor is it neutral"*, implying that it depends on how it is produced and deployed, benefits and liabilities – both in the short and long term. Global warming and climate change may be consequences of the misuse of technology. The planet needs urgent solutions to protect the environment, which reminds the second law of technology, "i*nvention is the mother of the necessity".* While technologies have brought many benefits to society, there is a turning point where the short-term benefits do not pay off the planet's long-term liabilities. Producers are rewarded for their ability to lower product costs and commercialise their products. Intermediaries (media, retailers, service providers) are rewarded in proportion to their ability to trigger new acquisitions. The greater the commercialisation rates, the greater the rewards, and consequently, the higher the emissions.

Emissions are released in proportion to the volume of goods produced, consumed, and disposed of. Technology is used to stimulate new acquisitions and facilitate the commercialisation process. Pervasive technologies transform the individual into a permanent consumer target. Climate change and global warming are consequences of the misuse of technologies by increasing production and consumption – without taking accountability for the long-term consequences on the planet. Technology becomes a root cause of the global emission problem since it helps multiply production and increase consumption rates.

Smartphone and desktop applications such as social media and video streaming are usually free in exchange for keeping the user engaged – aiming to maximise opportunities for a third party. The service provider monetizes by engaging the users, while another third party (vendor, retailer) realises the sale. The users' time becomes a commodity - lives have been wasted, addiction, and negative behaviour, are some of the outcomes. Algorithms can be tailored (e.g., ML/AI applications) for collecting and tracking user behaviour. New acquisitions take place, and later, the user may even regret what they bought, as they did not need it in the first place [466].

The release of emissions does not characterize technology companies and their products (or services); however, they are key participants in the emissions process. Every economic segment uses digital technology in many forms –prospecting the mining process, controlling and monitoring procedures, manufacturing, delivering, billing, and easing the logistics complexities. Developments in systems integration (software and hardware), robotics, and automation enabled industries to triple output and reduce costs. Thus, technology companies become freeloaders on the global emission problem, like most of their counterparts in the service sector. There is a carbon footprint for every product manufactured, and every transaction triggers a service provider in the upper stream energy sector to burn more fossil fuels.

A small portion of technology focuses on health, medicine, and improving the planet or the community. The Health, Pharma, and Meditech segments together represent 3.65% of the estimated distribution of companies worldwide in 2020 [435]. The number of patents in environmental-related technologies (in 2020) represented 1.81% of the total IP worldwide [467, 468, 469, 470]. The benefits brought by many technologies do not outweigh the liabilities caused to the environment in the long term. Promoting indiscriminate productivity, uncontrolled consumption, and enabling more comfortable lifestyles at the expense of the environment are neither the best approach for the planet nor the people. Most stakeholders (e.g., high tech, higher education, media) tend to emphasise the benefits and hinder the liabilities of technology.

Digital technology has layers of abstraction, making it even harder for the public to distinguish benefits from liabilities, trusted and non-trusted sources, and media biases, creating extra roadblocks to reducing global emissions. Any entity can make unfounded assumptions, invoke one of many ambiguous standards, use a modelling tool, and claim “sustainability”. They may use poor data, present inconsistent results, and still make their way to the media.

4.3.4 LAW AND REGULATIONS

Energy legislation is a long journey that has not started yet. States are social constructs with geographically demarcated territories, protected by sovereignty and thus indivisible [471]. On the other hand, the atmosphere is a global common-pool resource, de facto a ‘*res nullius’* accessible to everyone as part of the Earth’s biosphere [472]. The specific combination and concentration of atmospheric gases physically shield the Earth from asteroids and ultraviolet radiation and stabilises the temperature, besides providing oxygen to all living creatures and carbon dioxide to plants.

Problems arise when many state laws and policies have been created to empower stakeholders to produce, consume and waste more and faster – and a vacuum of legislation protecting the atmosphere. The need for re-imagining sovereignty is central to climate change [471]. The global competition, the need for resources to run the heavy state machine, and the thirst for manufactured products from the public forced organisations to search for the least possible production costs, which translates to unclean methods [473]. Consequently, pollution disperses in the atmosphere and changes its concentration and physical properties, creating a high risk of harming Earth and humankind.

Electricity generation has been considered as one of the major sources of global emissions, followed by agriculture, industry, and transportation [474]. Over the last century, the state created a strong monopoly scheme for supplying electricity to the public. It created the largest network on Earth, took over a century to build, with deep financial, technical, and environmental ramifications. It is heavily based on unclean methods (combustion of fossil fuel), neither replaceable nor compatible with low-carbon lifestyle. On the contrary, in the search for higher exports, and taxes, governments incentivise the unlimited use of electricity, by providing low prices, and reliability. The existing policymaking system becomes a root cause of emissions since it protects the status quo and does not allow changes.

Legislations for lighting started in Europe and North America towards the end of the nineteenth century and then replicated around the globe [475]. Many countries have undergone law and policies change over the last few decades. Market liberalisation, restructuring, encouraging renewables, decarbonisation, carbon offsetting, and mitigation policies [476]. Despite being evident that global emissions continue to rise steadily [366] and climate change is a real threat [365, 385], inefficient policies are still in force, therefore contributing to the worsening of the problem.

Humanity has long used the atmosphere as a sink for waste with little concern for the long-term consequences to the planet. The problem of overexploitation of commons has been widely covered in the literature [477]. The realisation that excessive GHG emissions can lead to catastrophic scenarios has not been strong enough to avert tragedy-inducing behaviours – spearheaded by the state and carried by millions of organisations worldwide.

Tragedy-inducing legislation encourages stakeholders to deploy minimum cost methods to reduce end prices without providing mechanisms to mitigate the environmental consequences. Electricity has always been treated as a national security matter, as it impacts every other economic sector. The government, the industries, and the entire financial system became extremely dependent on electricity. The existing legislation protects the major producers, consumers, and intermediaries – and is ineffective in protecting the global commons, the atmosphere, and the environment.

Mapping territorial responsibilities for emissions can be challenging due to states' sovereignty and the absence of scientific methods to measure emissions remotely accurately. GHG emissions disperse in the atmosphere reacting with other gases, making it challenging to disaggregate and track provenance. Establishing causality becomes difficult, so regulation becomes challenging [471]. Once dispersed, it affects the whole planet, impacts human society, and crosses state boundaries and jurisdictions [478]. Thus, the global GHG emissions problem is a global commons problem untapped by current laws and regulations [479]. [472]

Since nation-states have become fully interconnected in the global supply chain, they cannot take an isolated position and faces risks of losing market and many other unknown risks. Unless all countries adopt cleaner methods under a global consensus, the tendency is to keep the status quo. Since no effective regulation favours clean methods, added to the fact that it is technically and economically infeasible to compete with the existing system, legislation becomes a root cause of the global emissions problem.

Electricity generation is a bottleneck for lowering production costs and is heavily trapped in regulatory and compliance guidelines. Millions of intermediaries benefit from low energy prices, which translates to emissions, which leaves no space for innovation toward a low-carbon lifestyle. Law and regulation become a root cause of global emissions when they stimulate decisions that favour the increase of emissions. Polluting is less costly than not polluting; thus, competing on equal terms with a system that deploys unclean methods becomes unfeasible.

4.3.5 POLITICAL SYSTEM AND NATIONAL STRATEGIES

The government can offer high living standards when the economy performs adequately. The entire set of legislation has been conceived to protect the local population and local institutions; however, international affairs also impact internal matters. The international competition is fierce and widespread, while the pressure from society for more benefits is continuous. Power brokers must leverage natural resources, geographic constraints, industrial capacity, international security, and diplomacy. Internally, the government must ensure healthcare, education, infrastructure and employment.

The natural solution is to increase GDP and promote local development. Otherwise, regional neighbours may grow faster and change the entire economic landscape. Lowering global emissions requires compromises on many fronts, including state, corporations, and individual affairs. The level of compromise is even harder for developed nations since the population has higher demands than in emerging countries. The greater the education level (HDI) and the living standards (GDP per capita), the higher the pressure from society to keep the existing benefits. Beyond local compromises, lowering global emissions requires a global consensus that currently does not exist.

Taking effective steps to cut emissions directly conflicts with the existing political model. Local leaders are evaluated by their ability to convey benefits to society in the short term. The pollical system encourages populism, so leaders tend to please the population to keep their positions and status quo. On its downside, it becomes a root cause of emissions since it encourages the continuation of the problem.

International business competition is another hurdle to overcome when combating global emissions. Supply and demand rule the international fossil fuel prices, although oil cartels interfere. The OPEC (Organisation of the Petroleum Exporting Countries) protect their interests from the East, and the supermajors group (from Europe and the USA) protect their interest in the West. The electrical sector remains strongly centralised, controlled by the state, and deeply influenced by oil and gas prices. Any manufactured product relies on fossil fuel as a primary source (coal, natural gas, oil, petroleum) or secondary resource (e.g., electricity, transportation). Modern societies have become dependent on fossil fuels. An escape from the fossil fuel lock-in has not yet occurred, and the timing is not yet set [480].

As part of national strategic plans to secure existing benefits for the community, corporations are encouraged to increase exports and productivity, leading to more GHG emissions, consumption, and waste. Strategic plans solve a localised problem and, in the meantime, create a bigger problem for the planet, leaving it unsolved.

Unless the population raise their awareness of climate change and its associated consequences, it is unlike the ecosystem will change on its own. The misalignment between national strategies and global emissions when the lobby to increase local emissions, supporting the industry, is greater than the need to cut emissions.

4.3.6 HUMAN NATURE

As people increase their income, they tend to adopt a high-carbon lifestyle. They can acquire more assets, have more options for products and services, easy living, comfort, mobility, time-savers, entertainment, and more. That is a natural tendency of the individual. People tend to prioritise short-term benefits, which creates a gap, a loophole that top corporations explore. They offer non-essential short-term goods and benefits in exchange for a profit. There would be nothing wrong if not for the consequences for the planet in the long term.

As media, marketing, and technology can change human behaviour, corporations use them in their best interest to fabricate new desires for the individual. During their schooling years, young people learn that their rights, desires and wants lie above the planet's consequences. In the search for “advancement and status”, people are trapped by pervasive technologies, enabling more tasks in a shorter time, stimulating acquisitions, negative behaviour, addiction, and naturally more emissions.

The industrial sector deploys low-cost methods, so the end price is low and affordable for the consumer. Since technology multiplies production and consumption, added to the massive exposition of ads and media, people take for granted that their consumption behaviours have no association with climate change.

No entity, no web application, no large institution is engaged in raising user awareness to avoid unnecessary acquisitions. They do not even know what it takes in the background to produce the goods and infrastructure to enable their high consumption lifestyle. On the opposite, they support and stimulate a high-carbon lifestyle, as they are beneficiaries of the economic model.

Suddenly, the high-carbon lifestyle has been incorporated as part of human nature, leading to indiscriminate production and emissions. Since laws and regulations promote low-energy costs, the natural tendency is for people to keep increasing consumption and acquisitions. In turn, it triggers the release of more emissions by the suppliers of electricity and fossil fuels.

4.3.7 GLOBALISATION

People have been trading goods and services since the Ancient Age - from luxury items (gold, spices, silk), slave trade, sugar, and more recently, petrol, oil, coal, and technology. The modus operandi and motivation have been almost the same all along. There are producers, consumers and intermediaries. The Industrial Revolution multiplied production, prioritized the lowest costs, disregarded the environmental impact, and created millions of intermediaries.

Global competition stimulates organisations to deploy the minimum cost methods to remain market competitive – which generally involves deploying unclean methods. Global exports increased by over 500% in the last 50 years [481]. There are 82,000 transnational corporations, not counting financial institutions [482, 483]. As long as global emissions keep rising and millions of containers keep crossing continents daily [56, 57], tracking emissions provenance with scientific methods becomes extremely challenging. Moreover, that concludes that the recent claims from developed countries on their ability to decouple GDP growth from emissions have little significance to the planet [448]. On the contrary, it backfires by helping the global problem worsen.

The exponential growth in trade over the last five decades is correlated to the level of carbon emissions for the same period. According to recent estimates, internal trade accounts for 20-

30% of the global GHG emissions [353]. It is increasingly rare to find a truly national product that does not involve components (services or tools) from other nations.

By analysing and comparing the treemap exports and imports among countries, it becomes clear how intertwined and complex the global value chain has become. A country that mostly exports raw materials (e.g., mineral ore, metals, oil& gas) stands a much higher chance of having a per-capita emission. For instance, Australia's treemap export is heavily based on mineral products (63.4%), metals, chemicals, gas, and others [484]. On the other hand, the importing countries become free riders on the emissions from the primary sector. They may be exporting electronics, computers, or specialised services (software, management consulting) and taking advantage of the economic model without carrying the burden of releasing emissions. So, global trading makes it extremely difficult to assign accountability for emissions.

As the entire supply change became interconnected, the claim that countries in Europe (or North America) have managed to lower their territorial emissions over the last decade becomes pointless regarding global net emissions since total emissions keep rising. Unless scope 3 of the Greenhouse Gas Protocol [99] is rigorously taken into account, claiming the possibility of decoupling GDP and HDI from territorial emissions by simulating data models based on assumptions is highly questionable.

Figure 54 is a Ven diagram showing the causes (innermost circle), sources, drivers and the seven root causes (outermost circle) of the global GHG emissions problem. It summarizes what has been discussed in this section.

Figure 55 shows the Ishikawa diagram of the Root Cause Analysis targeting the GHG emissions problem. The main root causes resulted from a series of exercises, including mind map exercises, brainstorming, affinity diagrams, and the Five Whys method, which has been sorted and adjusted to fit the Ishikawa Diagram. This diagram was created as a result of many trials and attempts until a comprehensive overview of the root causes was achieved.

4.4 MAIN CONTRIBUTION OF THIS STUDY

Climate change is a real and tangible dilemma [19, 20], whereas global emissions are still a complex problem to be solved. This paper brings the following contributions to the field:

(1) Provides a unique and comprehensive overview of global emissions' causes, sources, drivers, and root causes.

(2) Supports the education of researchers and the public on the many ramifications of global emissions;

(3) Sheds light on the huge gap between territorial and global emissions and global sustainability (and net-zero);

(4) Untangles the differences between emission freeloaders, emission producers, and passive beneficiaries of emissions.

(5) Formulates that the emissions problem is a global-common management dilemma and cannot be solved individually by each nation-state.

(6) Features the seven root causes of global emissions, providing specific context for each.

(7) Establishes the pressing need for formal and global authority to manage global emissions and establish accountability for mitigation.

(8) Clarifies that the strategy of transitioning to renewables alone coupled with carbon offsetting, besides being inefficient, is providing a disservice in mitigating the global emissions problem.

(9) Accentuates the conflict of interest between tech giants and lowering global emissions; Digital advertising industry (e.g., Google, Facebook, Twitter), e-Commerce (e.g., Amazon, eBay, Alibaba), multimedia device vendors (Apple, Microsoft), all profit by stimulating more consumption and acquisitions, thus, inducing more emissions.

(10) Emphasises that the drivers of emissions (intermediaries) have become the biggest roadblock to lower emissions; since large transnational corporations have greater access to public opinion (media, ads), they can easily manipulate and keep the status quo.

4.5 CONCLUSION

The global GHG emission problem has multiple root causes, whereas tackling one aspect in isolation is ineffective. Since there is no global authority to impose regulations and enforce compliance, and nation-states are protected by their sovereignty rights, it becomes clear that depending on the existing stakeholders, the tendency is getting worse.

Thus, the release of the emissions is (i) a response to the demand from the population, which has been magnified by the intense use of technologies, transforming needs into wants; (ii) a consequence of poor industrial transformation methods to lower production costs and meet governments' strategies, and (iii) a consequence conflicting interests involving large multinationals (e.g., tech giants versus oil & gas supermajors) and governments.

Solving the global emission problem requires a framework of tools, planning, and conditions that challenge existing governments, constrained by the current political and economic model. The problem has ramifications beyond governmental spheres, and current tools are inefficient and slow. A global consensus has never been reached over the last three decades. Apart from the pledges to meet IPCC guidelines, which become pointless if all countries fail to follow as a group, there are no signs of credible planning in the pipeline.

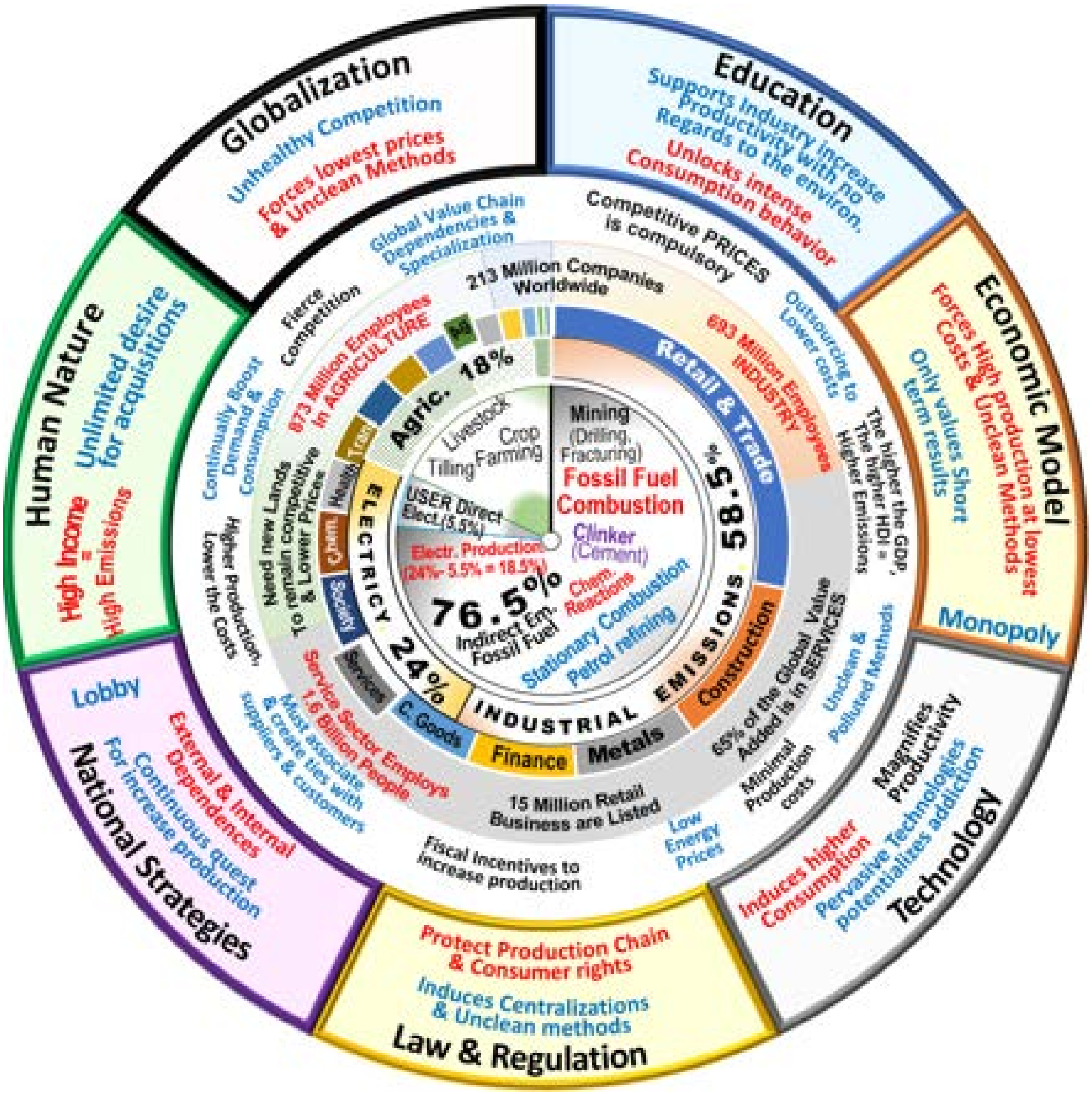


Figure 54: Causes, Sources, Drivers and Root Cause of Anthropogenic GHG

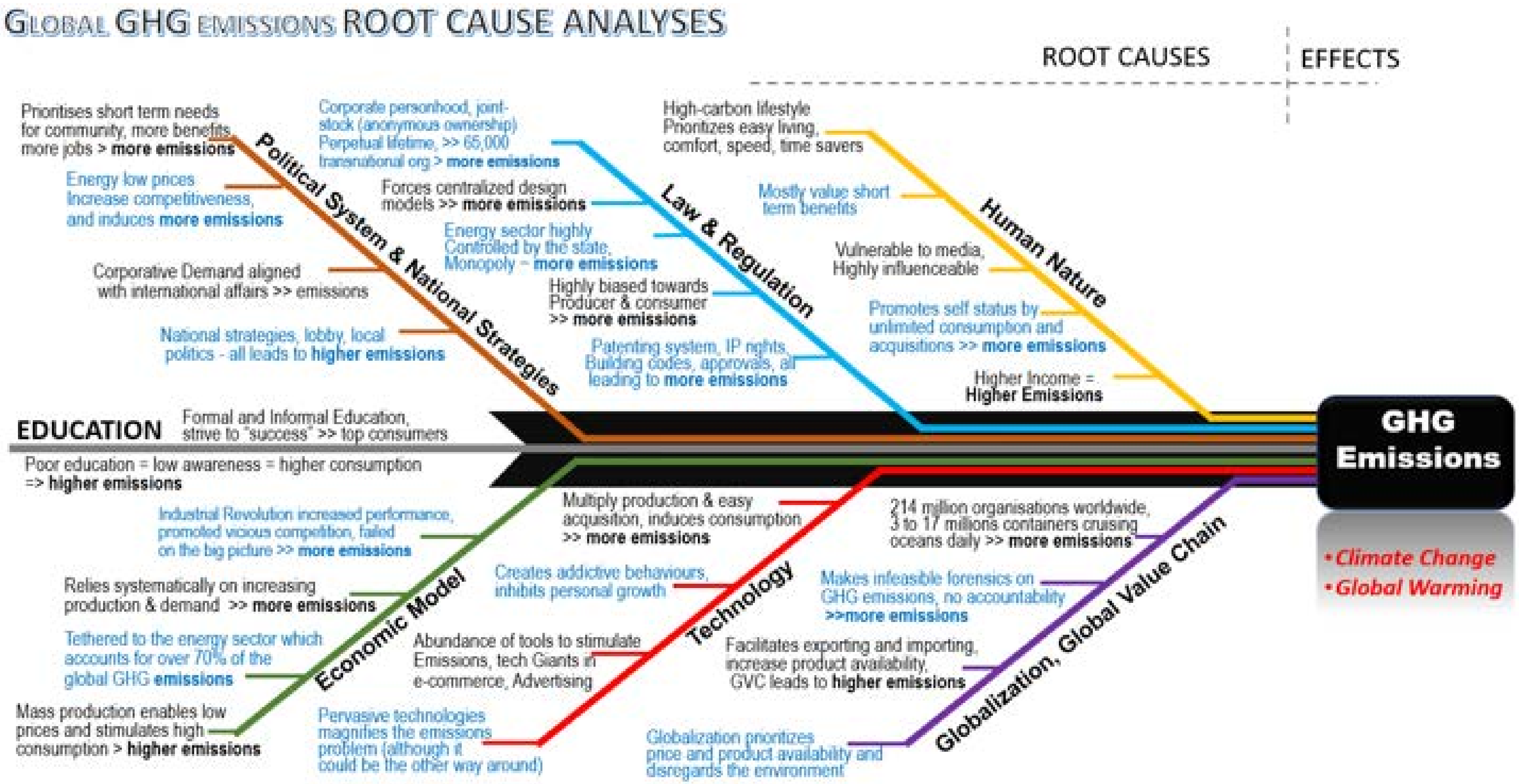


Figure 55: Ishikawa Diagram for Root Cause Analysis – Global GHG Emissions Problem

Chapter 5: BAIoT & ADCx Models and BAIoTAG Framework

Whereas Chapter 4 detailed the global emissions problem, this chapter presents a path to the future. It presents three studies that complement each other: the ADCx model, BAIoT system, and BAIoTAG framework. Together, they provide an overall methodology for solving the emission problem from the electrical sector.

The ADCx model is a new concept of DC power distribution through a small-scale decentralised design model, autonomous, away from the public grid. Furthermore, to increase the ADCx performance and competitiveness, the BAIoT system adds automation, intelligence, and user education. The IoT agents collect the data, aggregate it, and publish results in the Blockchain network. Conversely, AI agents subscribed to specific channels can assess, process and carry out several tasks, such as prediction, fault diagnoses, providing user or network feedback and re-publish in the Blockchain.

Lastly, the BAIoTAG framework creates the foundation and conditions upon which the whole system can work together. Over the next sections, the ADCx, and BAIoT models are presented, followed by the BAIoTAG framework.

5.1 Autonomous DC Picogrids, Nanogrids and Microgrids: The ADCx Model

Abstract

Users are compelled to use the public grid that deploys unclean methods, such as burning fossil feedstock. The existing power system has been built around low electricity prices at the expense of the environment and future generations. It remains centralised, monopolised, and strongly controlled by the state. The claim of lowering global emissions through the deployment of renewables can be perceived as a strategy to prolong the status quo. Global GHG emission levels keep rising, almost steadily, despite Covid-19. This paper introduces the ADCx model as an approach to overcoming the global emission problem from the power utility segment. It builds upon small-scale, decentralised, autonomous and sustainable DC power plants. On a hierarchical design model, users can share power resources, collaborate, and take corrective action toward becoming sustainable. It is a bottom-up approach, starting from a house level (*Picogrids*) to a street block (*nanogrid*) and up to an entire suburb or region (*microgrid*). The ADCx model has been strategically conceived with minimal dependence on legislation changes and surrounding stakeholders. The system architecture, building components, advantages, and limitations are discussed. The ADCx model is followed by two other studies by the same authors, the BAIoT system and the BAIoTAG framework. To the authors' best knowledge, this is the first time a comprehensive study has been proposed explicitly to solve the GHG problem in the electricity industry.

Keywords: ***ADCx, small-scale DC power plants, microgrid, nanogrid, picogrid***

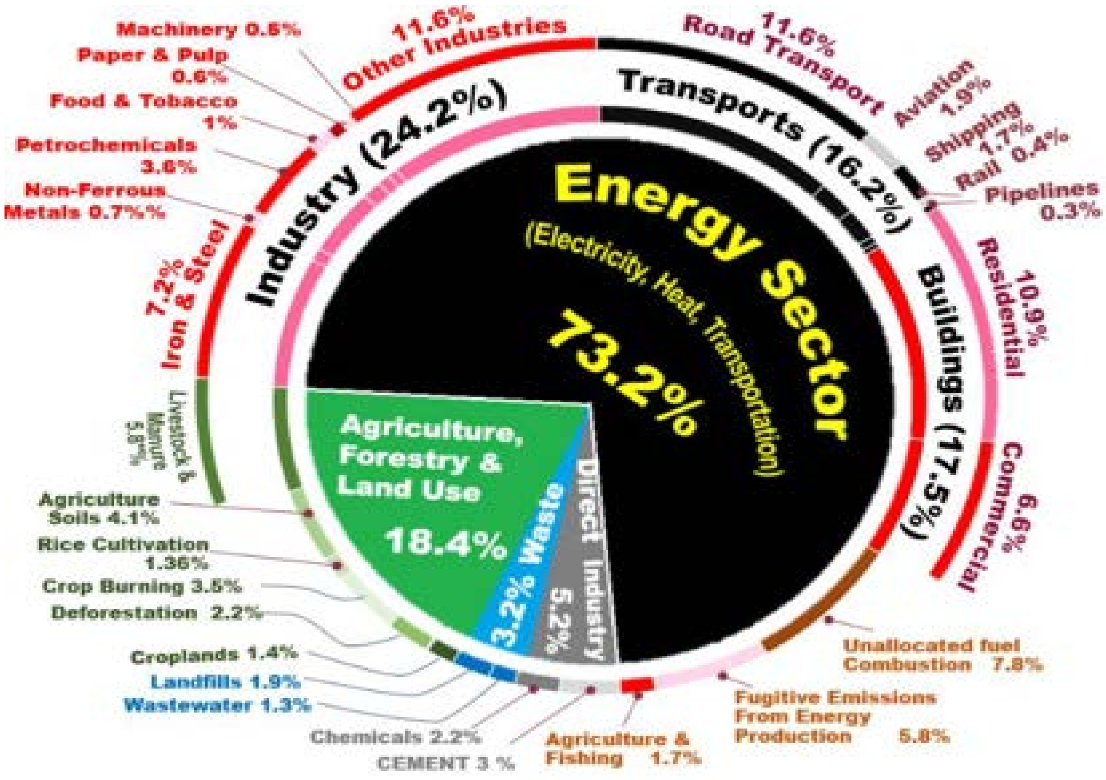
5.1.1 BACKGROUND

Since the wave of industrialisation, human development has become dependent on fossil fuels for mobility, better living standards, time savings, and communications. Most products and technology would not exist today if not for hydrocarbon extraction. It holds high energy density, is reliable, abundant and can be found on every continent. Contrary to groundless belief, fossil fuel is far from scarce. As put by [39], "*we have far too much oil, gas, natural gas and coal - not too little*". Alternatively, echoing the words of another subject matter expert, "*the Stone Age came to an end, not because we had a lack of stones, and the oil age will end not because we have a lack of oil"* [36, 42]. Exploring, mining, drilling, transporting, processing, and burning fossil fuels remain strong economic activities. Demand for natural gas, oil, and coal has recently spiked to record levels. Oil reserves dynamically change according to the law of supply and demand and the tendency to keep growing – at least for the foreseeable future [485, 486, 487].

Every manufactured product relies on fossil fuel, directly or indirectly - from metals to medicine pills, from concrete to multimedia. Global price competition has been present in human history since the inception of money – and has become a pre-requirement to reach global competitiveness. Under the status quo, 73.2% of the GHG emissions are resultant from the energy sector (electricity, heat, and transportation). Figures 56 and 57 show estimations of global emissions breakdown per industrial sector [422, 488].

Whereas the global population is likely to reach 10 billion around 2055, the consumption rates for the extra 2 billion people and the socio-economic improvements in developing nations will likely cause a massive environmental impact. Considering that the group of developed countries roughly account for 13% of the world population [489], even in the best-case scenario, where ambiguous pledges assumed by some rich countries to reach net-zero emission by 2050 become a reality, the final impact on global emissions will be hardly

Figure 56: Global GHG Emissions per Sector (1990-2016)
Sources: Climate Watch, the World Resources Institute



noticed. History shows that consumption tends to follow the same trend when societies move up the socio-economic ladder.

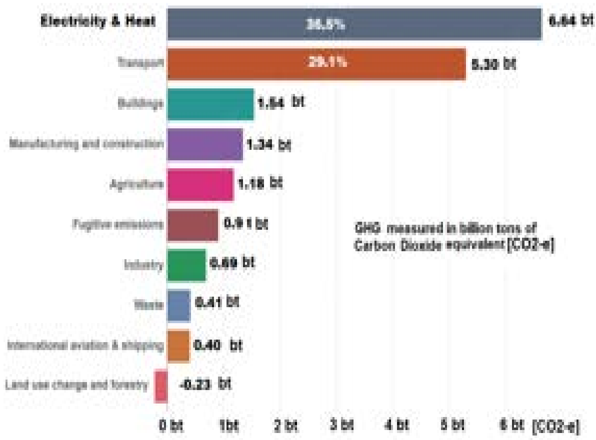


Figure 57: Global GHG Emissions Per Sector
Sources: Climate Watch, the World Resources Institute

Governments have been presenting conflicting goals for lowering CO_2 emissions. Whereas the gradual increase in demand and consumption helps increase GDP indicators, it also helps increase emissions. Corporations rely on low energy prices and high availability to become internationally competitive. The emissions released are proportional to the volume of goods (and services) produced, consumed, and wasted. This implies that society can no longer rely on governments to solve environmental problems since they have developed a strong dependency on corporations, leading to many conflicts of interest.

The main causes of GHG emissions from the electrical sector are related to the combustion of fossil fuels in thermal plants. The combustion of fossil fuels without proper mitigation mechanisms, such as better filtering systems or carbon sequestration (or capturing) processes, is rooted in the economic model, political system, culture, education, legal system, and others. There are many variables, unknown risks, and explanations for why the problem worsens.

This study argues that solving the emission problem requires a multi-action addressing all the root causes simultaneously. Some actions are linked to individual behaviour, while others require a collective approach. Raising environmental awareness through education and reducing unnecessary acquisitions and consumption is key to lower emissions. Fossil feedstock must continue to be used as fuel as long as cleaner methods are properly deployed. Renewable sources can play an important role when misleading propaganda is removed. The worst-case scenario is the continuation of the status quo. Unless there are some mechanisms to manage the global commons beyond state boundaries and new design approaches capable of permeating sovereignty rights, the tendency is the continuation.

5.1.1.1 On Governmental Strategies To Mitigate Emissions

Electrification started towards the end of the 19th century when incandescent lighting and motors were the only applications. Today, there are hundreds of applications, dozens of types of motors and a myriad of electrical appliances. Technical decisions were viciously influenced by business and political interests [490]. The result was severely biased laws favouring large, centralised, fossil-fuel-based power plants. When added technical aspects, legal complexities, high levels of investment, lobbying, uncertainties, and monopoly - all factors combined left no room for environmentally friendly solutions. Whereas waves of deregulation, restructuring, liberalisation, and privatisation took place, the global emissions keep rising as if nothing had happened. From an environmental perspective, the bulk of the legislation set for the electricity segment remains nearly the same during the last century.

Since low electricity price is a major driver for local economic development, deploying large and centralised plants has become the leading strategy. The government has been sponsoring a monopoly scheme to ensure energy security, whereas the producers have no option other than deploying fossil fuels to keep lower prices. The whole supply chain in the energy sector is expected to meet strict guidelines (key performance indicators - KPI) enforced by the regulators. High availability, quality, and fast demand response are top priorities and low prices. With such constraints, deploying fossil fuels (oil, gas, and coal) obtained via unclean methods has become the only viable solution, leading the electricity industry to become one of the major sources of global emissions.

It is important to distinguish the causes, drivers, sources, and root causes. The causes of emissions refer to the dozens of processes involved in the primary and secondary sectors for extracting, preparing, processing, and delivering the fossil fuels to the power plants – plus the combustions in the power plants. Thermal power stations (coal, oil, or gas-fired) convert heat from the combustion to produce high-pressure steam connected to the electrical generator.

Clean power plants cannot compete on equal conditions with thermal plants since mitigating emissions would require several extra steps, leading to extra costs. Deploying cleaner methods requires a new design concept, infrastructure, and many user behaviour changes. Large-centralised-unclean (methods) and small-decentralised-clean are not compatible. One focuses on prices and availability, the latter on finding a sustainable condition, a middle point between needs and wants. These are conflicting designing goals with distinct constraints leading to different network architectures, and there is no mid-ground to satisfy both.

With all the AC infrastructure ready and running, it creates a barrier to innovative and cleaner solutions. It will always be less costly to exploit the existing infrastructure than to build a new one to satisfy environmental needs. Any feasibility study that compares these two antagonistic approaches, considering only short-term benefits, the levelised cost of electricity (LCOE), is biased and contaminated. A fair comparison would require that both solutions share the same goals (sustainability or low prices, not both).

Governments often provide subsidies and incentives around infrastructure deployment, site building, transmission lines, and ancillaries as a strategy to increase consumption. Historically, governmental departments have commissioned or overseen power stations, followed by a handover process to a service provider. Natural monopolies undermine any form of competition, partially explaining why global emissions have been continuously rising [491, 385, 336]. Electricity production accounts for 24.5% of total global emissions, whereas heat, transportation and electricity combined account for 73.2% of the global emissions (Figure 56) [492].

On the other hand, the key government strategies to lower emissions are the deployment of renewables and carbon offsetting for companies. Both have been ineffective and contributing to the problem getting worse. Most recent data shows that the CO_2 emissions trend keeps rising [385, 336, 491]. The carbon offset market and credits may be helping nations to get around their responsibilities, but it is certainly not helping to reduce global emissions [400]. The following sub-section further explores renewable sources

5.1.1.2 ON RENEWABLE SOURCES

The transition to renewables projects the idea that renewable sources would solve the global emissions and climate change problems. However, this is far from reality. Transitioning to renewable is suiting many stakeholders, except for lowering global emissions. It lowers the public pressure by inducing false hope so that business can be carried as usual. In the meantime, it creates extra space for more opportunities, brand and product greenwashing. On its downside, despite the many pledges from corporations and nation-states' representatives, emissions keep rising.

Being renewable is neither a guarantee of being sustainable nor reliable. Moreover, it is risky to group all the renewable solutions under a single category. Each renewable source has a series of constraints and different emission payback times (EPBT) [493, 494]. A few solar panels on a rooftop can be perceived as environmentally neutral (although it can be misleading); however, several millions of panels in a single solar park requiring continuous wet cooling using freshwater is another story entirely. The scaling factor provides new perspectives – and how to calculate the EPBT is another challenge.

In some cases, wind, geothermal, biomass (biofuels), and hydrogen (fuel cells) can have serious environmental consequences, even worse the regular fossil fuel burning [495, 496, 497, 498, 499]. Beyond GHG, terrestrial, aquatic, and aerial biomes must be accounted for with all species, organisms, and biodiversity when assessing the environmental impact. For instance, over 20 years, methane (CH_4) and nitrous oxide (N_20) can have global warming impact dozens of times worse than carbon dioxide (CO_2). Fortunately, the concentration of these gasses is smaller than CO_2. Nevertheless, CO_2 can remain in the atmosphere for a thousand years, while CH_4 and N_20 only for a fraction of it [500].

Large hydroelectric plants may inundate huge areas, disrupting wildlife habitats and creating enormous environmental and social instability. In many cases, this results in decimating fish species, forcing the relocation of entire indigenous communities, wasting fertile lands, and depleting entire biomes [501, 502]. However, many lifecycle assessments, academic papers, and agency reports have been published classifying hydroelectric systems as clean energy, which is highly debatable. Small hydropower plants could be an ideal local solution in some cases. However, extending this concept to large power plants can be disastrous. Although such an option may not be available for most developed countries, it can be catastrophic to the environment and have global consequences [503, 504, 505].

Nuclear plants are reliable baseload power solutions and operate with low carbon emissions. However, the 'operation' is only one of the ten stages of a cradle-to-grave life cycle assessment of a power plant (construction, mining, milling, fabrication, enrichment, operations, radioactive waste handling, long-term disposal management, decommissioning, and long-term management for then decommissioned waste).

The average construction timeline for commissioning a nuclear power plant is around eight years. It involves a colossal volume of cement, steel, and earthmoving, which is highly emission-intensive with an immediate environmental impact. Decommissioning and decontamination stages can easily take another 10 or 20 years and can be very resource-intensive and a major environmental concern. The average operation lifespan of a nuclear power plant is in the range of 40-50 years. Besides, accidents do happen, and when they do, the impact of nuclear plants can devastate the planet and future generations. The environmental payback may take hundreds of years [494, 506]. Accidents, terrorism, water cooling problems, waste management, construction, every aspect carries associated risks. Nevertheless, since CO_2 emissions are negligible during operations, that has become the leading argument put forward by biased stakeholders. Any lifecycle assessment that omits key environmental aspects, unsupported by a reliable community of subject matter experts in every stage (logistics, construction, decommissioning, waste management), can be considered pointless and misleading.

About 2% of the solar power reaching Earth's surface is transformed into wind [507] – and a fraction of that is converted into electricity. Large-scale onshore wind farms are another debatable case of echo sustainability. Like nuclear plants, the carbon footprint during operation is also very low, although this is only a fraction of the total emissions taken during the entire life cycle. Besides, there are many other aspects to be considered. The environmental impact of wind power is immediate, starting with the construction, where cement, steel, and earthmoving are energy and resource-intensive, causing a direct impact on local biomes. A few studies have indicated that if the GHG budget is calculated short- to mid-term (e.g., ten years), wind farms can cause more climate impact than coal or natural gas. On the other hand, if a long-term perspective (e.g., 1,000 years), power would have lower emissions than coal or gas [499, 27, 495]. By that time, civilisation will have many other needs, wants, and constraints.

Typical towers with horizontal axis wind turbines (HAWT) can reach over 80m high and average 200 cubicle meters of reinforced concrete in the foundation [508, 507]. A single HAWT may be equivalent to the construction of 50-100 houses in terms of embodied energy. Energy density, intermittence, global value chain and logistic complexities, data quality, and other factors contribute to uncertainties when quantifying wind farm emissions. Large ground installation area per wind tower (average 2 acres), transportation constraints due to the blade sizes (e.g., 40 to 70m long), hazardous material, new accessing roads, every event must be factored in when assessing environmental impact [509]. Then, many tons of steel, cement, earthmoving, killing migratory birds and immediately impacting wildlife [510, 511].

Offshore wind farms offer some extra benefits; however, there are still uncertainties regarding the environmental impact on fishes and aquatic biomes. Various concepts around wind power include small wind turbines (SWT), Darrieus, Savonius, and H-rotor. A thorough environmental impact assessment is key to determining when wind power can become a better option when compared to other electricity generation methods.

Even solar power systems cannot be regarded as completely environmentally neutral. The adverse environmental impact of large-scale solar parks with several millions of panels includes land clearance, habitat loss, toxic material, disposal, and intense water usage for solar thermal plants (CSP) requiring incessant cooling. At first, it may sound like a minor impact; however, most of these gigantic farms are in remote areas, like deserts. Using fresh water in arid locations for cooling or cleaning purposes, where reserves are very low, can be a major problem. Some "wet cooling" solar power plants use more water per unit of electricity produced than a conventional fossil fuel plant. The impact of the disposal of damaged and decommissioned panels with a cocktail of hazardous materials is another major concern. However, most of these constraints can be mitigated with some extra costs.

When responsibly planned and all environmental aspects mitigated locally, renewable power solutions can contribute to the environment in the long term. The worst-case scenario occurs when publicity replaces science – which may help to explain why global GHG emissions keep rising, despite all the propaganda on renewables.

5.1.1.3 WHY SOLVING THE EMISSIONS PROBLEM FROM THE ELECTRICITY INDUSTRY REQUIRE A NEW DESIGN APPROACH?

The existing power grid (AC) holds many characteristics to benefit users, such as 24x7 availability, robustness, resiliency, reliability, and low prices. It powers every industry, business, and public and private facilities, helping increase GDP and the development of the economy. These attributes are made possible because the AC system exploits every possible planning strategy to lower costs, e.g. lean design model, centralised and large coverage areas for minimum deployment costs, and fossil fuel burning without efficient emission mitigation mechanisms.

If only the financial aspects are considered and given that there are no laws enforcing clean methods, finding a lower-cost competitive solution for the AC that delivers the same benefits and, in the meantime, is pro-environment becomes impractical – and contradictory. Because delivering low prices and being pro-environment lie on the opposite sides of the design strategy spectrum.

On its downside, the liabilities for the AC implementation include (a) polluting the planet by releasing a huge volume of GHG emissions, (b) undermining competition, (c) creating environmental impacts that compromise species, habitats, and future generations, (d) leaving no option for the population other than harming the planet in exchange for short term benefits, e.g. better living style, and (e) since energy is relatively low-cost for the developed nations and readily available, it becomes a strong motivator for the increase in consumption and acquisitions – which leads to more emissions.

Since the global emission problem has multiple root causes, tackling only one aspect and disregarding others can induce different problems. For instance, roughly fifty years ago, scientists warned about the serious effects of ozone depletion on human health and the environment. In 1987, the Montreal Protocol on Substances that Deplete the Ozone Layer was in force, referred to as a landmark agreement that has successfully reduced the global production, consumption, and emissions of ozone-depleting substances (ODSs) [512]. However, it solved one problem and indirectly created new problems since fluorinated gases (F-gases) exacerbate the GHG effects [513]. Fluorinated gas emissions in the USA have increased by about 90% between 1990 and 2020. The HFCs proposed as a substitute for CFCs are now in phase-down and phase-out processes in many countries [514, 515].

Moreover, the following aspects should also be taken into consideration:

- Global actions to reduce emissions have been proven ineffective, and there are no credible plans in the pipeline to overcome existing roadblocks.
- The deployment of renewable sources has been inefficient and helped to postpone the solution since the historical emissions levels [491, 385, 436] keep rising steadily.
- There are several conflicting agendas between governments, corporations, and the community. Governments have to increase productivity to raise GDP, leading to more emissions.
- The existing power grid with large and centralised power plants, de-facto controlled by the government through concessions (monopoly), has become unsustainable and a leading cause of climate change;
- Since emissions are released in the same proportion as products (and services) are produced, commercialised and disposed of.

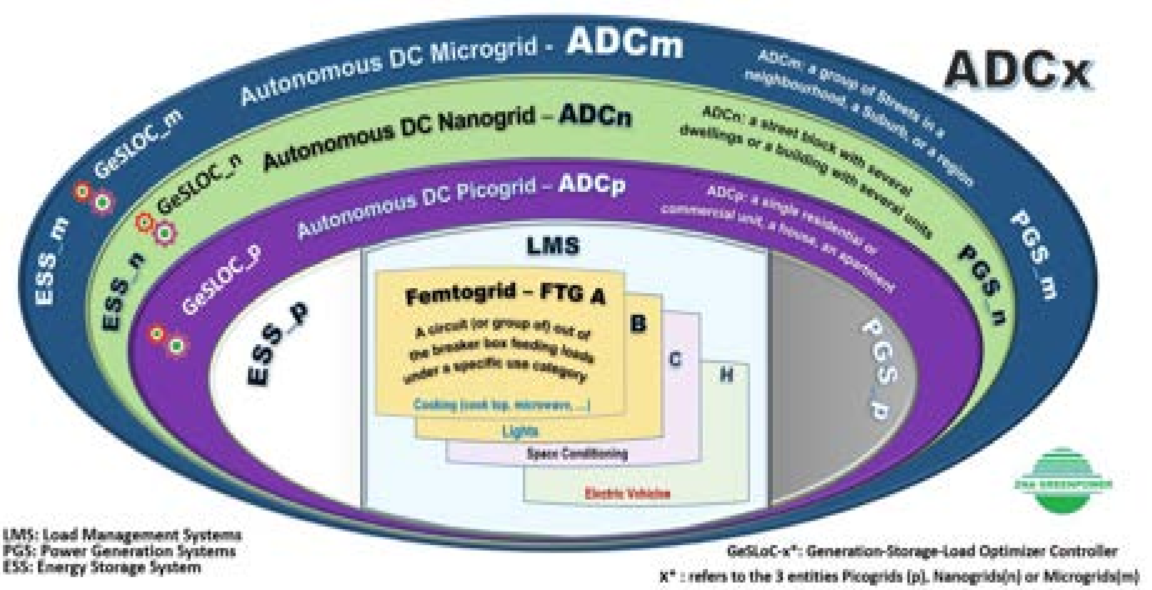
Thus, As long as the existing stakeholders remain in power under the same economic and political structure, the chances of lowering global emissions are slim. The ADCx model is presented in the next section as an approach to solving the root causes of the emissions problem.

5.1.2 ADCx Systems Overview

The foundational idea of the ADCx model is to motivate users to become sustainable in their households or neighbourhoods without relying on the public infrastructure. It builds upon resource sharing, responsible consumption, reduction of network losses and, when possible, deployment of clean methods for electricity generation. Resource sharing implies having a common DC bus with storage and flow control capabilities. Responsible consumption requires some mechanisms to monitor and provide continuous user feedback.

Figures 58 and 59 display the hierarchical concept of the ADCx ecosystem, consisting of three main layers, *microgrids (*ADCm), *nanogrids* (ADCn), and *picogrids* (ADCp). Each of these entities has several sub-units and a controller: (1) power generation system (PGS), (2) energy storage system (ESS), and load management system (LMS). The GeSLOCx is an engine that controls and interacts with these three sub-units. GeSLOCx is also used for integration, optimisation, administration, and management purposes. There is always a

Figure 58: Autonomous DC Microgrids, Nanogrids, Picogrids – ADCx Conceptual Model



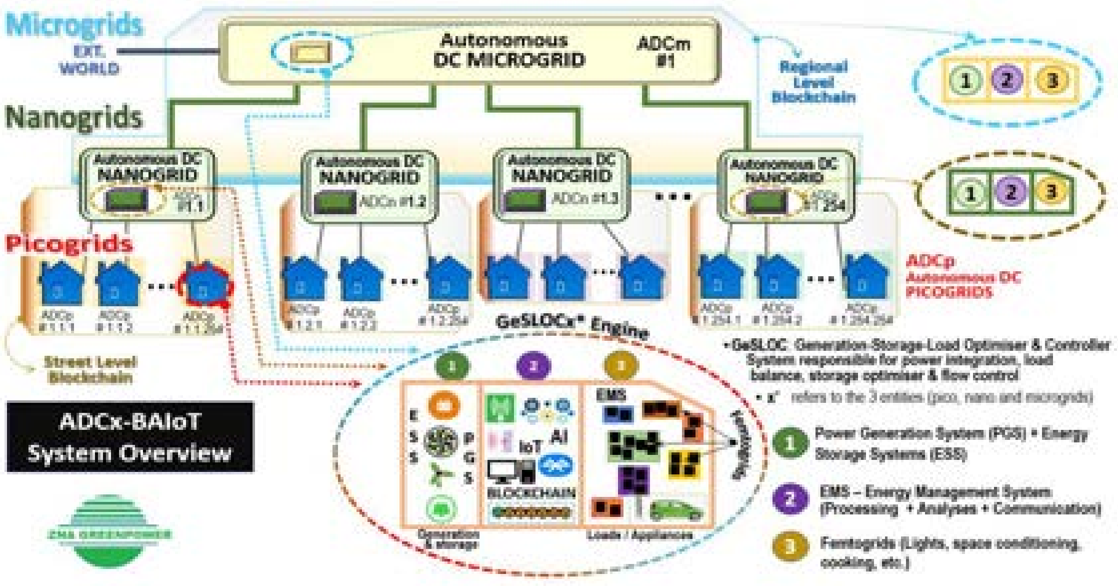


Figure 59: ADCx- Systems Architecture

GeSLOC unit dedicated for each entity, e.g., *microgrid* (GeSLOC-m), *nanogrid* (GeSLOC-n), and *picogrid* (GeSLOC-p).

ADCx counts on the stratification in a peruse category, whereas each use category is designated a specific '*femtogrid*'. Users can prioritise activities that best serve their goals within a time frame. The continuous network monitoring coupled with usage stratification enables customised feedback to users, such as fault diagnosis, reducing waste and raising users' awareness of consumption.

The acronym ADCx stands for autonomous DC power plants, where the low cap 'x' designates the type of infrastructures such as *microgrids (m), nanogrids(n)* and *picogrids(p)*. The ADCx system has been conceived to provide the infrastructure, so users and communities can benefit from electricity without depleting the planet. Being isolated from the AC grid is fundamentally important to the model. Autonomy can be achieved locally or through a group of users sharing common resources.

Figure 60: A microgrid with 03 nanogrids and 38 picogrids

Figure 61 shows the coverage area for each of these three entities. It shows a microgrid with three affiliated *nanogrid*s. *Nanogrid#1* is comprised of 11 houses, hereafter called *picogrids*.

Nanogrid#2 has 15 picogrids. And *nanogrid*#3 is a vertical multi-dwelling residential building comprised of 12 *picogrid (*apartments).

5.1.3 ADCX SYSTEMS ARCHITECTURE AND BUILDING COMPONENT

The foundational building blocks of the ADCx model are the *microgrids*, *nanogrids* and picogrids. A *picogrid* represents a single unit (e.g., a house); a *nanogrid* interconnects several affiliated picogrids within a street block; a *microgrid* links several *nanogrids* within a suburb or neighbourhood. Most of the work published on *microgrids*, *nanogrids* and picogrids does not apply to this study since they are connected to the AC grid and have very distinct goals (e.g., power control, frequency control, optimisation). A description of each major building block of the ADCx model is provided below.

5.1.3.1 Autonomous DC Microgrids

Power microgrids have existed for over a century since electricity was first offered as a public service through a utility company. The period 1880-1890 is widely known as the electrification decade. The Manhattan Pearl Station, built by Thomas Edison around 1882, initially serving 82 customers and covering a few street blocks, was essentially a *microgrid* [516, 517]. The first wave of electricity consumers were hotels, theatre houses, and department stores. Next, local governments perceived the benefits of lighting in the public space [518]. Several small power plant projects took place worldwide at the time, in Germany, France, Belgium, the USA, and Japan, and each one was an independent *microgrid* [519, 520]. Over the next century, *microgrids* grew larger, regulated, and integrated to become the existing power grid. More recently, the *microgrid* concept was resurrected as a localised solution for a particular group of consumers, or special case, within the low-voltage AC distribution systems [521, 522, 523]. In this case, a microgrid is perceived only as an accessory to support the existing AC system to optimise costs and improve demand-response in specific use cases.

Specific literature for DC *microgrids* has been found concerning autonomy, voltage variation, standardisation, synchronisation, the uncertainty of power source availability, and load control [524, 525]. Distributed cooperative control for DC *microgrids* has been proposed by [526]. The concept of Resilient Electric Infrastructure Technologies, R-EICT, is aimed to improve resiliency through 5G/B5G mobile edge computing on overall optimisation of autonomous decentralised cooperative control of DC *microgrids* [527].

Autonomous DC *microgrids* sharing the same coverage area of the traditional grid, purposefully disconnected from it, have not been found in the literature yet (at the time of writing).

Within this study, a *microgrid* can refer to a decentralised approach to solving the DC power requirements for a group of *nanogrids* for a specific area. It may refer to a (i) site facility equipped with DC power source, distribution and storage systems, (ii) a coverage area serving two or more affiliated *nanogrids*, (iii) a networking system that integrates communication, power generation and loads under a unified platform, or (iv) a legal organisation such as association or cooperative formed by the network participants within a specific geographical area.

Best engineering practices followed by a thorough environmental impact analysis (EIA), and feasibility studies, will determine site location, size (capacity), coverage area, redundancy, protection, safety and how to best support the local community. In ADCm, the primary focus is sustainability aspects and then economics.

The ADCx model suggests that a *microgrid* may serve up to 250 *nanogrids, or* 62,500 picogrids. The key objective in restricting sizes is to avoid monopoly and keep away stakeholders interested only in lowering prices at the expense of the environment. As long as a *microgrid* fulfils the environmental constraints and consumer needs, the size becomes second nature. The building blocks include the site facility, affiliated *nanogrids,* the electrical gears and ancillaries for interconnecting the *Nanogrids*, cables, terminations, safety devices, communication components, routers, switches, and operating system, power source, storage systems, loads and more.

A *microgrid* requires a network operator formally constituted under a legal structure. An organisation qualified for such undertaking must handle the network operations, maintenance and monitoring aspects. Service provisioning, onboarding customers, assurance of key performance indicators, all these tasks can be outsourced or directly run by the *microgrid* organisation. It depends on the microgrid's design, size, constraints, and limitations. It assumes that affiliated *picogrids* and *nanogrids* are capable of reaching a consensus and electing a board of directors. Then, this board will establish the protocols and guidelines for the operator. Each *microgri*d institution must be tailored to satisfy the specific needs established in the consensus protocol. A *microgrid* can be considered a cooperative, not-for-profit organisation or any institution - as long as it has effective rules to ensure sustainability, service quality, safety, and prevent contractual breaches among users or the operator. Responsibilities, rights, obligations, organisation types, contractual terms, insurance, and risk mitigations will follow applicable regulations, depending on each jurisdiction.

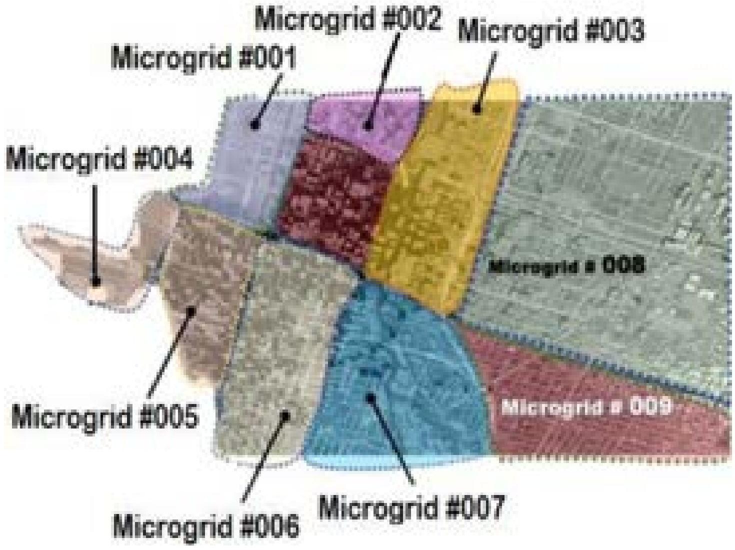


Figure 61: Nine Microgrids in a densely populated area (CBD)

Figure 61 shows a densely populated metropolitan CBD area covered by nine *microgrids*. Figure 62 shows how six *nanogrids* can be interconnected to a *microgrid*. In geographical terms, a *microgrid* can easily cover hundreds of street blocks, an entire neighbourhood, a small town, or a low-density region. Moreover, a *nanogrid* comprises several individual units (picogrids) within a street block or units within a multi-unit building.

5.1.3.2 Autonomous DC Nanogrids

The *nanogrid* concept has been explored for decades in power distribution. Often, it is related to power management, system control, convertor types, energy trade, the ability to work on both islanded and grid-connected modes, and remote applications [528, 529, 530, 531]. Some authors refer to *nanogrid* as a household, a group of houses, remote communities, rural areas or as an islanded application. DC *nanogrid*s have also been proposed over the past few years. Different topologies and configurations of nanogrids have been explored by [530], and determining the best solution on a case-by-case basis can be challenging. However,

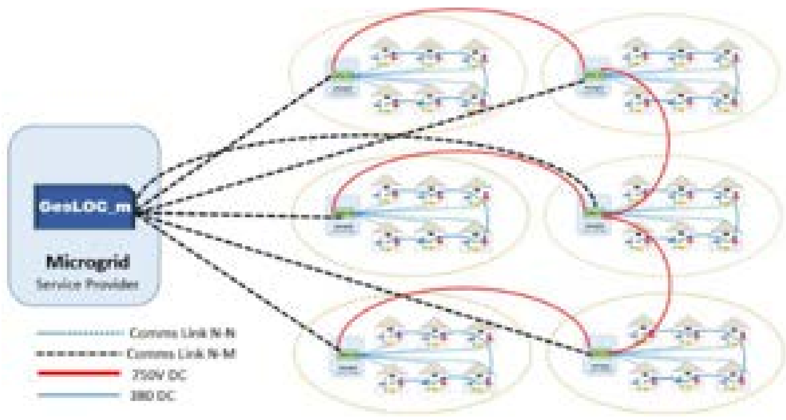


Figure 62: DC Microgrid with 6 Nanogrids

only when connected to the AC grid and featuring the capability of operating on islanded mode [532, 533]. In a few special use cases, autonomous DC *nanogrids* have been proposed for remote and isolated areas [534, 535, 536, 537]. Within the ADCx model, a *nanogrid* can refer to an area, a site, or a network that integrates several units (e.g., houses) or an organisation. A *nanogrid* site does not necessarily require a dedicated physical site; however, it must have enough space for power devices, terminations, communication, and control systems. The *nanogrid* network integrates a collection of *picogrids* under a single electrical, communication and distributed computing platform. The main goals are to support *picogrids* in reaching their power requirements and sustainability.

Figure 63 : low-density area with several nanogrids

A *nanogrid* area is restricted to a street block or a multi-unit building, and it may serve a mix of residential, commercial, and small industrial facilities (Figure 63). The building blocks of a nanogrid system include all the picogrids, the electrical loads, their interconnection (e.g., cables, terminations, safety devices), communication devices, operating system and, depending on the case, power sources or storage systems. The *nanogrid* system enables the peers to communicate, exchange private data, trade (or barter) electricity on their own and import or export electricity to other *nanogrids* via a *microgrid* operator. Like a *microgrid,* a *nanogrid* must be legally constituted as a small organisation by its founding members. It may elect an operator who will provide operations and maintenance services and keep the system operating smoothly. The *nanogrid* organisation must be formed by the neighbours sharing the same street block. It may be operated by their associates or through delegation of power to a third party, a service provider elected through a consensus for a specified period.

5.1.3.3 **Autonomous DC Picogrids**

The concept of *picogrid* as a small-scale power plant has not been found in the literature at this writing. However, a few authors used the term (*picogrid*) in different contexts, referring to small power generation sources (electric vehicle battery, solar thermal) or as the name for a measurement system in smart-home applications [538, 539, 540, 541, 542].

Within the ADCx model, a picogrid refers to a single site, such as a house, flat, small commercial or small factory facility. It includes all the circuitry for powering appliances, storage systems and interconnection with power sources. A *picogrid* site has a sole proprietorship and can be located in urban or rural areas. Each circuit must be terminated in the breaker box and named after a *femtogrid*.

The building blocks of a *picogrid* system include several *femtogrids*, power sources, storage devices, distribution panels, power metering, cabling, earthing, control and communication or safety gears. Ideally, a picogrid should be able to operate autonomously and reach sustainability independently. However, these conditions carry technical and financial challenges, which may become preferable for a *picogrid* to be interconnected with other peers (via a *nanogrid* network). There are several value-added benefits for a *picogrid* becoming part of a peer-to-peer distributed network, improving network resilience, energy trading (or energy bartering), strengthening collaboration with the community, sharing lessons learned, facilitating the exchange of information, and improving habits, and more.

5.1.3.4 Femtogrids

A femtogrid is a circuit (or group) for a specific usage category. It has a defined functionality and identification, serving all the loads within a category. It includes cables, breaker(s), outlets, protective accessories, earthing connections, or terminations. Use categorisation is an essential aspect of the ADCx model for energy savings, facilitating monitoring, classification, prioritisation, fault diagnosis, and control management. Figures 09 and 10 show nine use categories, or nine *femtogrids*: (a) lighting, (b) food preservation, (c) cooking and water heating, (d) labour-saving and mechanical tools, (e) education, communication, gaming (f) space cooling and heating, (g) hygiene, (h) outdoor entertainment and (j) electric vehicles. Whereas a massive rewiring can become undesirable for an existing facility, many options are available for home energy management systems. Alternatives to rewiring are further explored under the Load Management System (LMS) section.

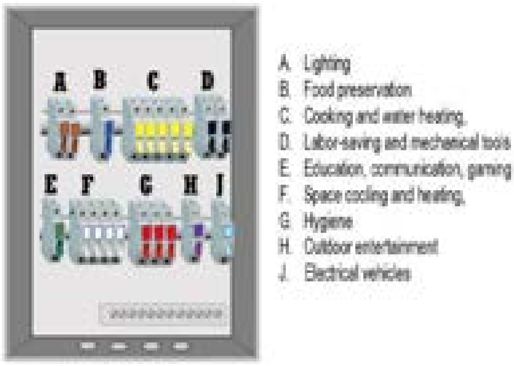


Figure 64: Femtogrids - Breaker Box

Figure 65: Use Categories - FEMTOGRIDS

5.1.3.5 **Power Generation System – PGS**

There are several options for choosing a power generation system within the ADCx model. Key factors include natural resources (e.g., wind, solar, fossil fuel, biomass), location, techno-economic factors, timing (prompt dispatch), capacity, and technical skills. Since there are three layers, there must be a corresponding PGS for each entity: (1) PGS-m for the *microgrids*, (2) PGS-n for the *nanogrids*, and (3) PGS-p for the *picogrids*.

Being renewable is not a guarantee of being carbon neutral. Each power source solution causes an environmental impact, which must be assessed on a case-by-case basis. Under ADCx, as long as all environmental impacts are properly mitigated, there is no preference to what type of power sources. However, only a comprehensive environmental impact assessment, including every single stage backed by subject matter experts, can establish what option fits best on a case-by-case basis [543, 544]. This study does not recommend power sources and storage options.

The importance to ADCx is to deploy clean methods to generate electricity, not the type of fuel. The system should be capable of supplying enough power to cover the peak demand for the site, whether it is a *picogrid*, *nanogrid* or *microgrid*. It should achieve a sustainability condition on its own or be associated with other peers. Solar photovoltaic, solar-thermal, hydrogen, small-size wind power, and biomass – all these options can be deployed within the ADCx model. Coal, natural gas, and oil can also be deployed if emissions are properly mitigated. ADCx prioritises clean methods for electricity generation, not fuel types (renewable or not).

Therefore, no large-scale solutions are compatible with ADCx, e.g., hydropower, geothermal, or nuclear power systems. In case multiple power sources are involved, the aggregation is done via the Power Aggregator-Controller and Optimiser (PACO) unit, controlled via the GeSLOC unit. These are further explored in the next section.

The concept of a Hybrid Renewable Energy System (HRES) has been extensively explored in the literature [545]. Combining multiple power sources helps to enhance efficiency, reliability, and flexibility. As previously mentioned, deploying renewable sources is not necessarily a guarantee of eco-sustainability. For instance, ethanol may come from sugarcane and is considered a renewable fuel source. In the meantime, burning on sugarcane plantations, tillage, and pesticides is all environmentally unfriendly. Any power source solution carries embodied emissions, and only a thorough environmental impact analysis can determine the level of sustainability.

Carbon capture and storage (CCS), carbon capture and utilisation (CCU), and carbon sequestration (CS) are some approaches under consideration. Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide. Biogenic-based sequestration (afforestation and reforestation) techniques can be, to a certain extent, considered mature and deployed immediately [546]. Bioenergy Carbon Capture and Storage (BECCS) is another promising *negative emission* approach discussed widely in the literature [547, 548]. CCS refers to capturing CO2 before it enters the atmosphere and storing it underground for a very long time [549].

5.1.3.6 **Energy Storage System – ESS**

The ESS solves the imbalance between power demand and power supply. During peak hours, consumers' loads may exceed the capacity offered by the power supply, and energy storage addresses that requirement. Conversely, the inverse may happen when the power production exceeds the demand. So, by storing the surplus of electricity, ESS can compensate for the stochastic nature, optimise costs and increase system reliability. Nevertheless, several trade-offs are involved when deploying ESS, including costs, lifespan, power quality degradation, response times, technical complexity, space, maintenance, and many others. Depending on design requirements, each entity, *picogrids*, *nanogrids* and *microgrids,* may require a dedicated ESS.

There have been intense developments in energy storage technologies, with varied options, in terms of capacity and features. That includes the (i) electrochemical types, such as batteries, e.g., lead-acid, lithium-ion, nickel-zinc (NiZn), nickel-metal-hydrate(NiMH), capacitor and super-capacitor, magnetic/ current energy storage systems, e.g., superconducting magnetic energy storage - SMEs, (ii) mechanical storage such as pump hydro, compressed air, flywheels. (iii) chemical storage such as fuel cells (e.g., hydrogen, ammonia), biofuel (e.g., biogas, bioethanol, biodiesel, algae, cyanobacteria, bio-hydrogen), and (iv) thermal storage (heat and cold), such as insulated reservoir, or cryogenic systems [550, 551]. Batteries are the leading option due to their low technical complexity and efficiency in keeping power stability [552].

ESS is an evolving industry, and prices are continuously dropping. The market average was around $137/kWh in 2020, dropping 87% over the past ten years [553]. This study neither compares ESS options nor recommends the best fit for each use case. The ESS should support the user to become sustainable and avoid interruption anytime.

The integration between power supply and storage systems has been explored in the literature on several fronts. For instance, solar thermal can convert sunlight into heat, create steam causing a turbine to rotate and store mechanical energy in a flywheel – or create electricity that can be stored in batteries. In special cases, ESS can be treated as the main electricity source. A hybrid energy storage system (HESS) may include multiple energy storage systems with additional features such as self-discharge rate, power density efficiency, lifespan, and more [554]. There are several design options to combine energy storage coupling architecture. The main goal for hybrid systems is to offer resilience and backup when the power sources cannot sustain the demand required.

When multiple storage systems are integrated, a control unit must be optimised for all the different voltage outputs. Within the ADCx model, the Storage Aggregator Control & Optimizer (StACo) unit continuously measures the different storage sources. It interacts with the GeSLOC system and the PGS units to decide how the unit should operate during different times of the day or conditions that can be triggered under certain events.

5.1.3.7 Load Management System – LMS

LMS refers to any computer-aided system that monitors, controls, processes, and displays real-time electricity consumption data to users. The term 'HEMS' (home energy management system) has been extensively found in the literature, mostly associated with smart home and smart grid applications [555, 556]. However, the ADCx model is not restricted to home applications, and the eco-sustainability aspect is the main driver. Therefore, the LMS acronym has been selected instead of HEMS.

Depending on the type of facility (household, business, factory), a typical electrical circuit may have many appliances. Installing sensors on each device throughout a household can be inviable. Grouping the appliances by use categories are highly important to ADCx; however, it could be costly and time-consuming for an existing house. The alternative is to use a Non-Intrusive Load Monitoring (NILM) [557, 343]system that uses Machine Learning algorithms. The options available for the LMS market can be overwhelming, e.g., Emporia Vue Smart Home, Powerpal, Smappee Infinity, TED Pro Home, Egauge, Efergy, Sense Energy Monitor, and many more. These systems are typically low-cost and can be used in the ADCx model. The technology is evolving, and results may vary slightly.

Current sensors are typically installed within the breaker box panel. They sample the electrical signal and send it to a hub, where data is processed, features are extracted, data is classified, and finally, the signal is disaggregated per each appliance. Most LMS brands use NILM technology for load disaggregation coupled with IoT technologies. Several LMS brands aim to improve efficiency, energy savings, fault detection, and send user feedback. Gamification is also a strategy to improve consumers' behaviour and motivate rational electricity consumption, which has also been suggested [558, 559, 560, 561].

Some LMS brands may take a long time to learn patterns and recognise an appliance. This often happens when several appliances share the same circuit, and the devices have similar electrical characteristics. Some appliances may be recognised almost immediately, and others may take a long time (e.g., months). Besides, appliances do change their electrical characteristics over time, and outputs may be impacted. The working and installation conditions may also affect consumption over time. For the present time, the higher the precision, the higher the costs. The trade-off between accuracy, technical skills, timing, and investment must be assessed.

LMS solutions typically involve hardware and software components under a single package. It collects the signal using sensors and transmits (via cable or wireless) to a hub where the signal is disaggregated. The raw data is stored (locally, remotely) or displayed via some application (mobile, desktop, tablet). From that point onwards, the GeSLOC system processes the data and interacts with other subsystems to take decisions and actions.

The loads for *microgrids*, *nanogrids* and *picogrids* are respectively linked to the LMS-m, LMS-n and LMS-p. For the microgrids, the LMS-m aggregates and manages all the loads from the affiliated *nanogrids*. Subsequently, the power loads for a *nanogrid* are aggregated in the LMS-n unit and are comprised of each *picogrid* associated with that *nanogrid*. Lastly, the loads for a *picogrid* are represented by the *femtogrids*, according to their use category.

In the case of *picogrids*, depending on whether it is a new facility, it may be cost-effective to deploy a load energy monitoring system capable of automatically stratifying the consumption according to the nine use categories previously mentioned (under the *femtogrids* & Loads section). In other cases, re-grouping the circuits according to each use category may be easier and less costly. Each jurisdiction may have specific regulations and codes, so re-arranging the wires imposes technical skills and compliance with regulatory codes.

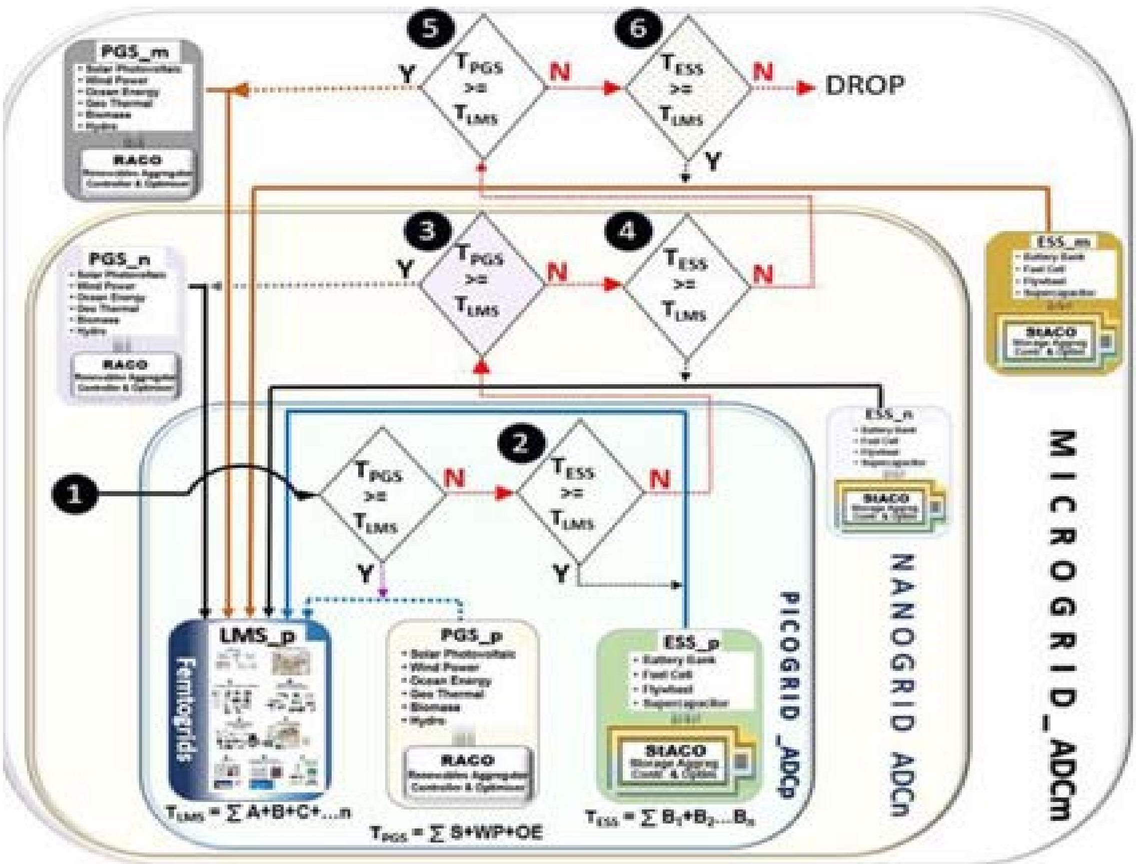
5.1.3.8 **Generation, Storage, Load Optimiser & Controller - GeSLOC**

The GeSLOC is the central control unit for the ADCx model. It collects data from each unit, including power generation (PGS), power storage (ESS), and load management system (LMS). It continuously captures the status of the power generation capacity provided by the PACO (Power Aggregation, Control and Optimisation) interface, compares with the load demand requirements (e.g., loads from each *femtogrid*), checks the energy storage status via the StACO (Storage Aggregation, Control and Optimisation) unit and makes timely decisions towards load shifting, load shedding and peak shaving. Typical decisions include: (i) deciding whether power generated should be stored or routed directly to the *loads*; (b) should part of the light circuit be switched off? (c) should the power being produced be capable of meeting all the demands? (d) Should a request be sent to the *nanogrid* operator for importing electricity starting in the next 12 hours? These are some native functionalities enabled by the GeSLOC engine.

The GeSLOC engine can feature more advanced functionalities. Under its native mode, it sends out network status, consumption, storage, and power source details, extracts (data web scrap) weather forecasting details, and presents them to users. Basic power forecasting can be implemented on its native move. On a more advanced level, it can conduct data analytics, send customised feedback, improve reliability, enable interactivity among prosumers, and many extra features. The advanced GeSLOC properties are covered in the BAIoT system, another study by the same authors that enhances the ADCx capabilities [562].

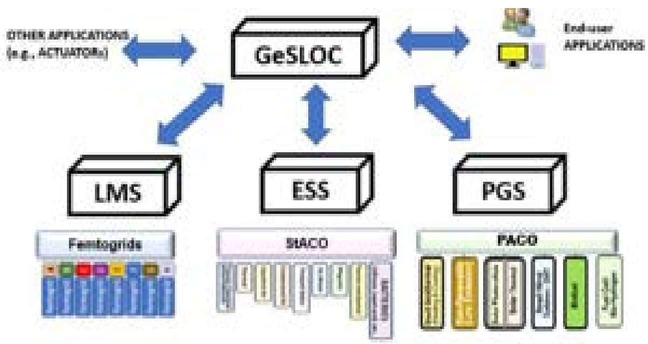
By keeping the user informed, GeSLOC helps raise consumer awareness and gain visibility on carbon footprint. It can take control of hundreds of background tasks, monitoring capacity, network conditions, and external conditions. The ability to forecast power demand and consumption is crucial for the ADCx model. Unlike other microgrid systems, the ADCx model does not rely on backup power from the AC grid. The model solely relies on its power generation and storage capabilities. So, the ability to forecast, optimise resources, keep the user aware, and facilitate interventions becomes critical to ADCx. Figure 65 shows the algorithm for the GeSLOC engine when operating under the

Figure 66: GeSLOC Native Algorithm (Functions)



native mode. When a *picogrid* load exceeds its local power supply capabilities, it first checks internally with its local energy storage system. Next, if the load exceeds the sum of the power supply plus the storage, it reaches out to the *nanogrid* power supply system. The same process repeats until it reaches the *microgrids*. If everything fails, then the load is dropped. Figure 66 provides an overview of how GeSLOC interacts with ESS and PGS for load balance and optimisation.

Figure 67: GeSLOC decision-making process



5.1.4 MAIN CONTRIBUTION OF THIS PAPER

Global GHG emissions are rising, even during Covid-19 times [385]. When removed media and propaganda, the simple metrics speak for themselves: all the current strategies for lowering global GHG emissions have failed. All the alerts and recommendations for policymakers under the IPCC's Fifth (AR5) report in 2014 have been misunderstood, miscalculated, or disregarded [563]. This paper addresses the emissions problem from the electricity industry and brings the following contributions to the field:

(1) Presents an alternative solution to energy distribution based on small and autonomous DC power plants isolated from the AC power grid;

(2) It promotes freedom for a system that pollutes and depletes the planet;

(3) Introduces a hierarchical design model including autonomous picogrids, nanogrids and microgrids, where they share resources and complement each other to improve efficiency.

(4) Introduces the concept of femtogrids, which is unique in the academic literature; the use of femtogrids helps to prioritise consumption by using categories, enabling the introduction of AI and ML algorithms to make more accurate predictions on a per circuit basis;

(5) Induces the creation of small power cooperatives where neighbours can share resources and knowledge;

(6) Transfers the accountability for sustainability from the state to the community and household level;

(7) Stimulates power consumption reduction and goods acquisitions, helping establish a middle point between needs and desires.;

5.1.5 CONCLUSION

Today, people have no other option than to continue using electricity generated via unclean methods, resulting from a monopoly scheme sponsored by the state and stimulated by millions of intermediaries worldwide. Solving the global emission problem requires raising awareness of the population to lower acquisition and consumption rates; the entire ecosystem works the other way around. From the corporative (or governmental) point of view, the higher the consumption, the better for business and the economy, and the higher the short-term benefits to society. However, this rationale is self-destructive since global emissions are released in proportion to the increase in consumption. These organisations are co-beneficiaries (directly or indirectly) from the increased consumption, implying more emissions.

This paper addresses the electricity industry, which has become the leading source of global emissions, by introducing the ADCx [564], a new conceptual design model providing the infrastructure for a local power system. It presents unique features and goals for supporting the community to become sustainable without waiting for governmental action to improve the current power grid. Instead of large, centralised, aiming at low prices and high availability, the ADCx focuses on small and decentralised power plants, prioritising the environment and society. The ADCx model postulates that emissions will keep rising indefinitely by keeping stakeholders under the same infrastructure, regulations, and motivations. It boldly asserts the proven inability of existing power brokers to lower global emissions due to conflicting interests and domestic and international affairs. The main objectives of the ADCx model are (a) to provide a path to sustainability without relying on the existing structure and stakeholders, (b) to raise users' awareness of their acquisitions and consumption, which translates into more emissions, (c) to rationalise consumption, and (d) to manage and control householders' carbon footprint. This study is part of an action plan, followed by another complementary study by the same authors, the BAIoT system, which focuses on analytics, intelligence, automation, and improving communications for the ADCx systems.

5.2 Reducing Global Emissions Through Blockchain, AI and IoT: The BAIoT System

Abstract: Greenhouse (GHG) emissions are released in proportion to the total production of goods, services, trades, and waste. Every organisation that produces goods, extracts and processes raw materials releases GHG missions. However, millions of intermediaries that do not release emissions are equally responsible for emissions since they stimulate or facilitate the increase in production, contributing to the global emission flow. Since every top-down attempt to lower emissions has failed, this paper presents the BAIoT system that provides tools to support households in taking accountability for their emissions. The BAIoT system complements the ADCx systems, another study presented by the same authors, as part of an action plan to solve global emissions. While the ADCx focuses on the network infrastructure, the BAIoT system builds upon communication, intelligence, and analytics, allowing incentives and extra benefits for users. Blockchain, IoT and Artificial Intelligence (BAIoT) work together, complementing each other to enable individuals or organisations to a faster transition to sustainability. To the authors' best knowledge, this is the first time a combination of technologies is explicitly proposed as part of a consolidated design to achieve sustainability for the electricity sector.

Keywords: Blockchain, IoT, AI, BAIoT, ADCx, BAIoTAG

5.2.1 INTRODUCTION

The global GHG emissions problem has multiple root causes, and addressing one in isolation while ignoring the others, becomes ineffective. Transferring the problem from the short to the long run is a poor strategy to mitigate environmental risks, as it may solve it in the short term and create a larger threat in the long run. The transition to renewables and the carbon offset market are the two main strategies recommended by IPCC for mitigating climate change. Considering that global emissions levels have been steadily rising [491, 362, 424, 425, 364, 368], it can be safely inferred that none of these strategies yielded positive results.

Every industrial segment depends on electricity, which led the energy sector to become the main source of GHG gas emissions [565] (Figure 68). Although the long list of environmental consequences is well-known, conflicting interests have contributed to the carbon lock-in problem, where self-perpetuation is the only certainty [480].

Most people fail to perceive the correlation between electricity generation, household acquisitions, and global warming [566, 567]. The higher the purchasing power (GDP per capita), the higher the consumerism orientation (HDI), the lower the environmental awareness, and the better for business development and existing stakeholders. Thus, global emissions keep rising for multiple root causes, as previously discussed by [564].

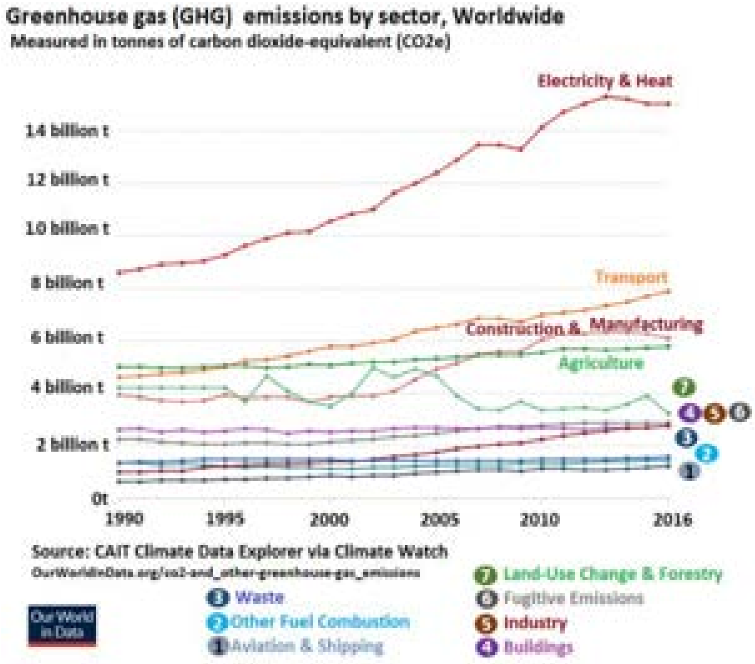


Figure 68 - Gas emissions per section in tonnes of CO2e

5.2.1.1 ON HOW INDIVIDUALS PERCEIVE ELECTRICITY CONSUMPTION AND GHG EMISSIONS

The correlation between gas emissions and climate change was reported over a century ago [72, 73], yet the general public still has difficulty recognising the link. From the time electricity started being offered as a utility service, by the end of the 19th century, the consumers' obligations were narrowed down to paying the energy bills. The responsibility of caring for the environment has remained unassigned since the time electricity became a line of business. GHG emissions are a global commons management problem [472, 479], which raises the question of whether electricity distribution was an informed decision or a mere opportunistic idea for financial exploitation.

Finding an appropriate location for power station facilities relies on fossil fuel accessibility, railroads lines, water access, risks of environmental disasters, costs, and many others. Whereas lowering costs was the top priority, power station planning decision-making has led to a large and centralised design model. Hence, power stations are often located remotely, away from densely populated areas.

A first problem arises when people cannot visualise and understand the magnitude of the problem (emissions). The educational system, agencies, and government fail to provide

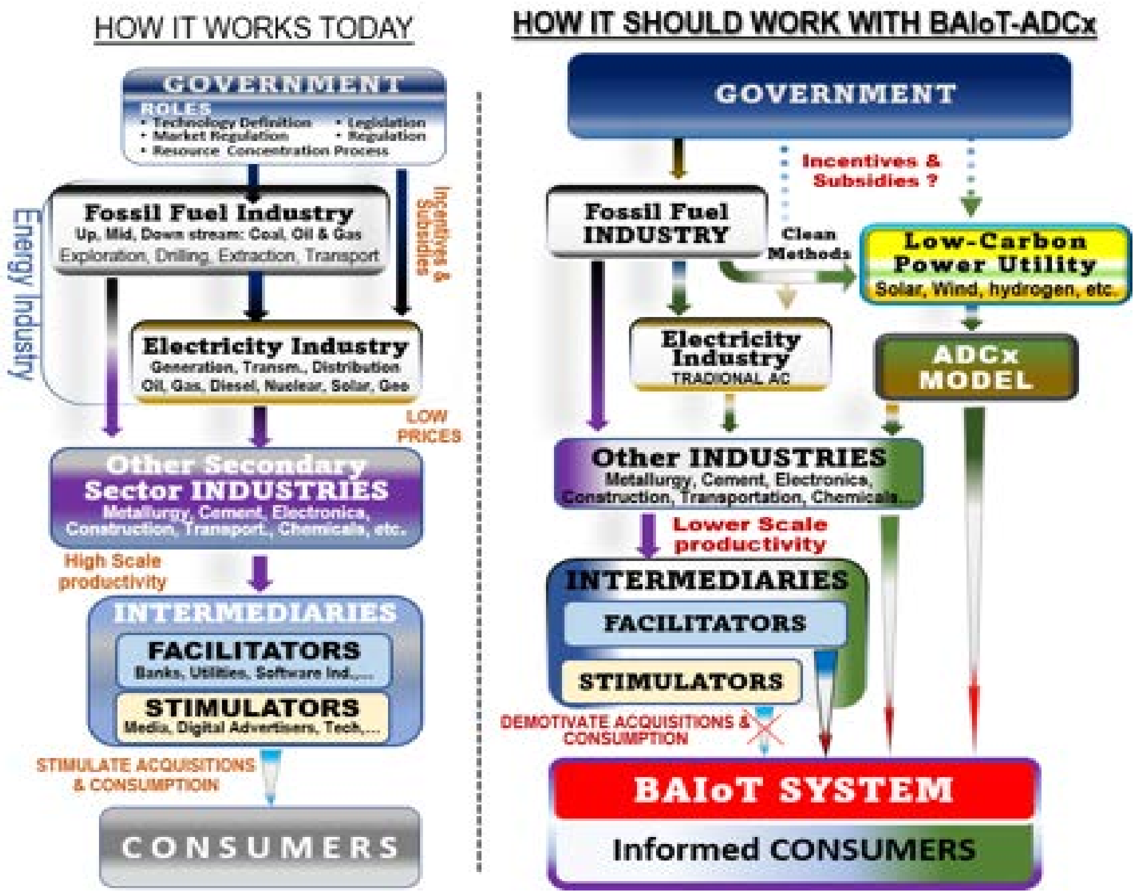


Figure 69: BAIoT demotivates acquisition and consumption and prioritize low-carbon lifestyle

details on the environmental consequences to the public. This happens for a good reason. As production, consumption, and waste rates increase, the electrical sector releases more emissions daily in response to the demands of individuals and organisations. Most of the largest institutions are exclusively rewarded by producing goods, stimulating or facilitating the flow of consumption. Thus, the conflict of interest is vicious, which has led to the status quo.

A second problem arises when people cannot sense their share of responsibilities for the flow of emissions. In power systems, the consumers initiate the flow of emissions rather than the electricity producers [454]. Fossil fuel combustion is the last step for the upstream service provider to meet the demand from the consumers. The consumer triggers fossil fuel combustion for every manufactured product, for the power required for running household appliances, or fuel for their vehicles.

Around 82% of the global emissions are related to fossil fuels and 18% to land-use change emissions (agriculture) [351, 352]. Of that, 76.5% are indirect emissions embedded in products from industrial activities, e.g. building facilities, services, and public infrastructure

- and not visible to the public. The part they could see and make sense of refers to household consumption, representing around 5% of the total emissions, the smaller part of a much bigger problem [352]. Since people cannot recognise their participation in the chain of events leading to emissions, they tend to disregard the problem, thinking climate change only affects elsewhere.

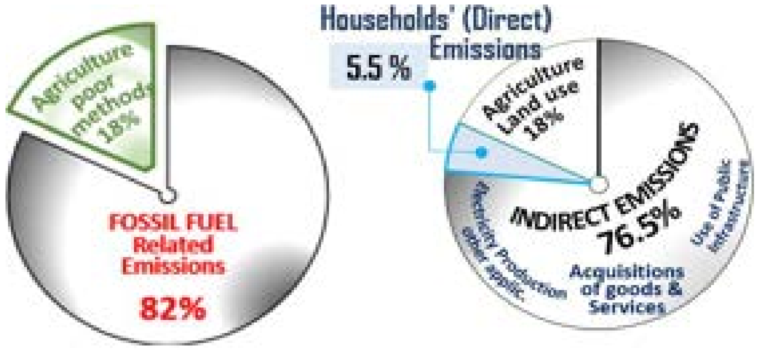


Figure 70: Direct (5.5%) and Indirect (76.5%) Emission Causes

Low energy prices have become much more important than climate change in the political discourse. The electricity suppliers deploy the lowest cost method to burn fossil fuels to satisfy government, vendors, and consumers. Since there are no laws against releasing a large volume of emissions, they please everyone, including themselves. Besides, electricity suppliers are subject to a legally binding contract - and must comply with key performance indicators, where low electricity price is a key factor in meeting the legal requirements.

A third problem arises when government sponsors intense propaganda around transitioning to renewables – as a type of vaccine able to stop climate change. However, the deployment of renewable has been taking place for a few decades and has no signs of lowering emissions. Whereas wind farms and solar parks have been deployed for several decades, global emissions continue to rise in the same quasi-exponential fashion (Figure 71). Renewable energy (like the carbon market) became a line of business exploited by industrialised nations for financial benefits, while their efficiency in lowering global emissions remains to be seen [491, 568].

Vendors count on millions of intermediaries to stimulate and facilitate acquisitions. Users acquire new appliances to keep updated with the technology, enhance social status, improve lifestyle, and compensate for negative emotions, addiction, or impulses. People may regret acquisitions made on impulse; however, digital advertising and media are intense and hard to avoid [569].

Householders have no motivation to reduce electricity. The media discourse is so intense that consumers might not even consider the possibility of changing habits to reduce electricity consumption. Although most utilities promote a load shift scheme to remove the power-hungry devices from peak hours, the total consumption remains the same. On the contrary, householders are systematically stimulated to keep acquiring more goods. This is the space where the big techs play a vital role in supporting government and boosting the Economy. This finding may help to explain why the largest transnational corporations are in the business of producing multimedia devices, digital advertising, eCommerce, and social media. They all rely exclusively on the continuous flow of acquisitions, consumption and profits.

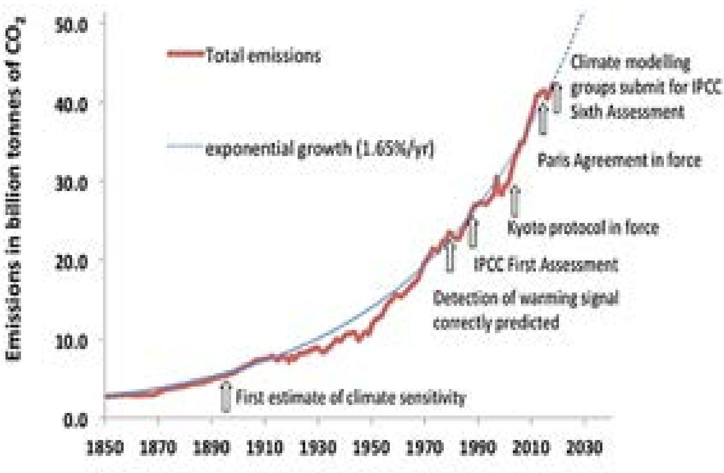


Figure 71 – Global CO_2 emissions- fossil fuels and land use change

The combination of low energy cost, unlimited supply, and high availability is the complete recipe to motivate householders to keep high consumption and trigger new acquisitions. A small part of the population, the early adopters, are flexible, open to new approaches, and willing to take pro-environmental actions; however, without infrastructure and tools, there is no hope. Then, a second group might still support pro-environmental actions, as long it does not interfere with their lifestyles. Lastly, there are those against any changes since they are the largest beneficiaries of the current system. Reversing this logic requires action planning covering many fields, such as education, tools, and new infrastructure - which is the core objective of this study.

5.2.1.2 On The Rebound Effect

The rebound effect refers to expected gains in energy economics, or net emissions, resulting from new technologies, new user behaviours, or any systemic changes that other subsequent events have compromised. Newer technologies often improve energy efficiency and decrease power consumption, leading to financial gains. However, the rebound of these benefits enables vendors to introduce other applications or trigger the user to buy extra goods or services, leading to more consumption and emissions.

The rebound effect has been intensively explored in the literature, extending beyond the energy efficiency and economic spheres [32, 570], such as natural resources, conservation, labour, time-savers, human behaviour, and household consumption. The rebound effect can be quantified as a ratio of the lost benefit compared to the expected environmental benefit when holding consumption constant [571, 572].

For instance, a householder deploys a new solar panel which may lead to lower electricity bills. The extra cash may lead households to afford an overseas trip, change their cars, or acquire any non-essential good that may neutralise or backfire the initial benefits. That may explain why global emissions keep rising despite all the propaganda around renewable sources

5.2.1.3 On Organisations and Their Relationships with GHG Emission

The corporative role brings mixed outcomes to society. Developed nations exploit the benefits of corporations in their best interest. The largest concentration of companies is in North America, Europe, and China, coinciding with the largest GHG emitters. Repeating the same pattern of another time, power brokers found ways to promote local development by encouraging the creation of more local companies. However, the consequences on the global commons (atmosphere, forests, waters) have been neglected.

Every enterprise has some degree of participation in the global emissions flow, directly or indirectly. Be it a governmental, community, political, educational, not-for-profit, technological, military, or religious institution. For instance, the military depends on the government, which relies on the corporations (for employment), that hangs on consumers, which leads to more production and emissions. A nonprofit organisation may depend on donations from industries that deploy polluted methods to create goods and services. Something is always extracted and burned at the end of the chain, and emissions are released. It is challenging to find a single institution isolated from the emission loop.

The key corporative actors in the global emission flow are the upstream energy suppliers, the stimulators, the facilitators, and passive supporters [564]. For the upstream energy suppliers and industrial sector, the following considerations shall be taken into account:

(a) Companies are not forced by law to disclose the precise amount of GHG emissions involved in running their activities, so they deploy any available method with no concerns.

(b) Limited liability (LLC) and public limited companies (PLC) protect the shareholders, so they cannot be held responsible for any management wrongdoing – this opens a huge gap for environmental risks while shielding the investors from being accountable for pollution.

(c) Companies are encouraged to keep low prices to remain competitive, which implies deploying the lowest cost production methods, leading to more emissions.

(d) No financial incentives exist for deploying cleaner methods, so polluted methods become the bottom line.

(e) There is no global reach legislation enforcing penalties for GHG emissions.

(f) With the rise in transnational corporations reaching (>65,000) and globalisation (>17 million containers), emissions accountability has become a grey area;

(g) In case a nation-state decides to deploy clean transformation methods, the production costs would rise, and the risk of losing global market share would be high;

(h) The pro-environment approach from a nation-state might not elicit any similar action or commitment from neighbouring countries.

Thus, it can be established that releasing emissions by the upstream energy sector is the natural alternative since the entire ecosystem forces them to lower costs to remain competitive. A group of 100 corporations in fossil fuel production are responsible for 71% of global emissions [451]; Top emission producers include China-Coal, Saudi Arabian Oil Company – Aramco, Gazprom-Russia, ExxonMobil-USA, Shell-Netherlands and many others.

Stimulators are not characterised by the intensity of their emissions but by their ability to engage customers in more acquisitions, which translates to more emissions. The stimulators of emissions include retailers, advertisers, media hospitality, travel, tourism and dozens more. They all create business by inducing more acquisitions, consumption, and thus, more emissions. The more they commercialise, the better for the business, and the greater the volume of emissions. Some of the largest emissions stimulators in the digital advertising industry include Google, Facebook, Twitter, YouTube, and others. Retailers include Amazon, Walmart, Alibaba, eBay, and others.

Emission facilitators provide the infrastructure and support for either energy suppliers or stimulators. Like the stimulators, they generate emissions themselves – however, they are key actors in the emissions' flow. Typical facilitators include the software industry, vendors of multimedia devices (smartphones, tablets, PC desktops), telecoms), banking, utilities, management consulting, and many others. Some large emission facilitators include Apple, IC Bank of China, JP Morgan, Microsoft, SAP, ATT, and Huawei.

The group of passive collaborators on the emission flow includes all institutions that help to maintain the existing infrastructure, the public services, public support service sector, government infrastructure (e.g., police, justice), public healthcare, nonprofit organisations, primary schools – and all essential services to the community. They do not profit from emissions; however, most are still beneficiaries since their funds come from energy suppliers, stimulators, or facilitators.

The relationship between business density and global emission levels indicates a strong correlation. The higher the number of corporations on a global scale [573], the higher the productivity and commercialisation, which leads to more global emissions [417]. Alternatively, in different words, in the search for faster profits, local development, and reducing personal liabilities, individuals encouraged by the state formed groups sheltered under the corporate veil, creating transnational corporations, which are capable of crossing boundaries, and blur emissions' accountabilities.

5.2.1.4 How to Create Strong Motivation and Enabling Tools Towards Pro-Environmental Lifestyle?

Examining each of the major actors in global emissions can provide valuable clues: government, fossil fuel industry, electricity industry, industrial segments, stimulators, facilitators, and consumers (Figure 52, Chapter 4).

The government's roles in the electricity segment include legislation, technology decisions, market regulation and resource concentration management. The government can enforce policies to meet national strategies, sponsor, authorise, or stimulate the construction of new power stations. It can also promote subsidies and fiscal incentives and control the electricity prices to users. However, as mentioned previously, the government has many conflicting roles in championing policies to lower emissions. Whereas their major task is to boost the Economy, where low energy price is key to triggering the flow of production and consumption, it also leads to more emissions. This contradiction of goals has been a leading cause for postponing the solution.

The energy industry (fossil fuel and electricity) responds to the demand of all the other industries (e.g., metallurgy, chemicals) and consumers. The higher the demand from the industries, the higher the electricity power, the higher extraction of fossil fuels, more combustion, and more emissions. They must comply with a demand-response timeframe as part of legally binding contractual terms. Besides, there is a chain of financiers, investors, and other stakeholders expecting their return on investment. There is no room for innovation when running existing power plant operations. Once the power station is up and running, there are no longer options to curtail emissions.

Stimulators mostly benefit from advertising and media, which systematically induces more business flow, leading to more consumption, acquisitions, and waste. Since stimulators are in the opposite line of business (creating more emissions), they have nothing to gain in the short term by adopting a pro-environmental approach. The same analogy applies to facilitators, such as banks, utilities, and the software industry, as they only profit when their clients are doing business. In the meantime, many large enterprises use carbon credit to obtain green certificates to greenwash their products (and services) and uplift the image of their organisations – as if they were helping the planet become cleaner. That is a clear scenario where green certificates, carbon credits, and carbon offset have not been effective in helping to solve the emissions problem. Instead, these approaches have become tools against society [457, 458, 459].

Thus, it becomes the only actor that can effectively influence the global emissions flow is the consumer. However, as stated previously (sub-section A), electricity consumers have no motivation to reduce acquisitions and consumption –and many might not even consider a remote hypothesis of changing habits to lower electricity consumption. Changing consumers' pre-conceived ideas requires several strategies covering various domains.

The existing power grid (AC) holds many characteristics to benefit users, such as 24x7 availability, robustness, resiliency, reliability, and low prices. It powers every industry, business, and public and private facilities, helping increase GDP and the development of the Economy. These attributes are made possible because the AC system exploits every possible planning strategy to lower costs, e.g. lean design model, centralised and large coverage areas for minimum deployment costs, fossil fuel burning without efficient emission mitigation mechanisms, monopoly scheme involving concessions for power generation, (ii) legislation, government benefits, subsidies, (iii) financial support and sponsorship, and (iv) a lean design model.

When planning a new low-carbon electricity power design, the following list of attributes can encourage users to move toward a pro-environmental agenda:

i) Ability to differentiate from the existing system by offering a series of advantages to users, such as rewards for achievements, household certifications, discounts, promote local business and increasing neighbourhood interactivity;

ii) Help to educate and raise awareness of the users. E.g., they should comprehend that the greater part of emissions refers to the acquisition of goods, services, and public infrastructure (76.5%); Household emissions represent 5.5% of the total emissions for powering appliances and fuel for vehicles; the remainder (18%) refers to agriculture;

iii) Enable peer-to-peer energy trading – or bartering;

iv) Improving integration within the community;

v) Promoting healthier lifestyles by reducing social media and electronics;

vi) Increasing awareness of products and services acquisitions that accounts for 76% of the environmental liabilities;

vii) Promoting house improvements such as insulation, sealing, and ventilation to minimise the use of air conditioning (heating and cooling);

viii) Raising public awareness on the correlation between productivity and emissions and waste;

ix) Determining the GHG carbon footprint for individuals, organisations, facilities, and compositions.

x) Establishing GHG footprint targets for organisations and buildings;

xi) Ability to deploy game theory to reach rational use of technology and consumption;

xii) Developing daily consumption patterns to improve behaviour, correcting misleading beliefs or assumptions;

xiii) Help the user to determine whether the use of an appliance is worthy of the liabilities caused to the environment;

xiv) Capacity to analyse historical consumption for individual appliances to determine performance consistency over some time (e.g., 6-month, 1-year, 3-year);

xv) Sending continuous user feedback warning any potential power waste, loss, or leakage;

xvi) Providing prescriptive and corrective analyses through feedback to improve user awareness;

xvii) Running real-time analytics predicting hours and 1-day consumption;

xviii) Ease the deployment of low-carbon energy supply (renewables);

This study proposes the BAIoT system, whose main goal is to enable informed consumers to reach net-zero emissions within their neighbourhoods; BAIoT brings extra functionalities to the ADCx model, another study presented by the same authors. Whereas the ADCx model provides a new infrastructure under a new design topology (small-size decentralised DC power grid), the BAIoT system focuses on analytics, intelligence, automation, collaboration, and secure communication. The next section provides more details on the BAIoT System

5.2.2 PRESENTING THE BAIOT SYSTEM

The BAIoT system aggregates Blockchain, Artificial Intelligence, and IoT technologies under a single structure, paving the way to greater energy and emissions awareness. In support of the ADCx model [574], BAIoT aims to (a) raise users' awareness of consumption and acquisitions, including emissions from daily usage and those embedded in acquisitions of goods and services or embodied in buildings, and (b) motivate users to lower their GHG footprint while avoiding the rebound effect, (c) provide continuous educational feedback to the user, and (d) exploit opportunities leading to greater network efficiency;

By providing tools and motivations, users can educate themselves, take control of their GHG footprint, improve habits, share information with peers, and find their middle point between essential and non-essential consumption and acquisitions. Newer features are vital to enhancing the benefits of the ADCx model so that they can outweigh those from the AC power grid.

5.2.2.1 THE BAIOT COMPONENTS

This section presents the three enabling technologies that can revolutionise the electricity industry. Blockchain, Artificial Intelligence and IoT can work together, complementing each other to optimise power generation, storage and distribution while supporting end-users to make better choices on acquisitions and consumption.

A transition to a low-carbon power system depends on new infrastructure, attributes, and features, followed by an appealing narrative to win the trust of prospective users - which matches the objectives of the BAIoT system covered in this section.

Many attempts have been tried to lower emissions while the global trend continues to rise steadily. In contrast with all previous attempts, this study boldly assumes that any successful solution should be built as far as possible from the status quo and follow a bottom-up approach. It must be spearheaded by the people and local communities and replicated worldwide. Also, it must overcome bureaucracy and geographical boundaries and offer undeniable benefits to society – such as sustainability.

Rather than being centralised and large, it must be small and decentralised. Rather than being robust and resilient, it should count on local power storage to overcome any instability from a stochastic nature of power generation. Local communities should have the resources, tools, and infrastructure to overcome power failures without relying on the traditional AC system, which is emissions-intensive and has become the major contributor to global emissions, thus, climate change.

Figures 72 illustrate how IoT, Blockchain, and AI agents can interact towards performing multiple tasks and ensuring data flow in a nanogrid environment. The Blockchain lies between IoT and AI technologies, enabling communication, security, and access control infrastructure among the several subsystems. IoT collects data at regular intervals from multiple subsystems, saves it on a local database, and sends data snapshots to the Blockchain on designated channels.

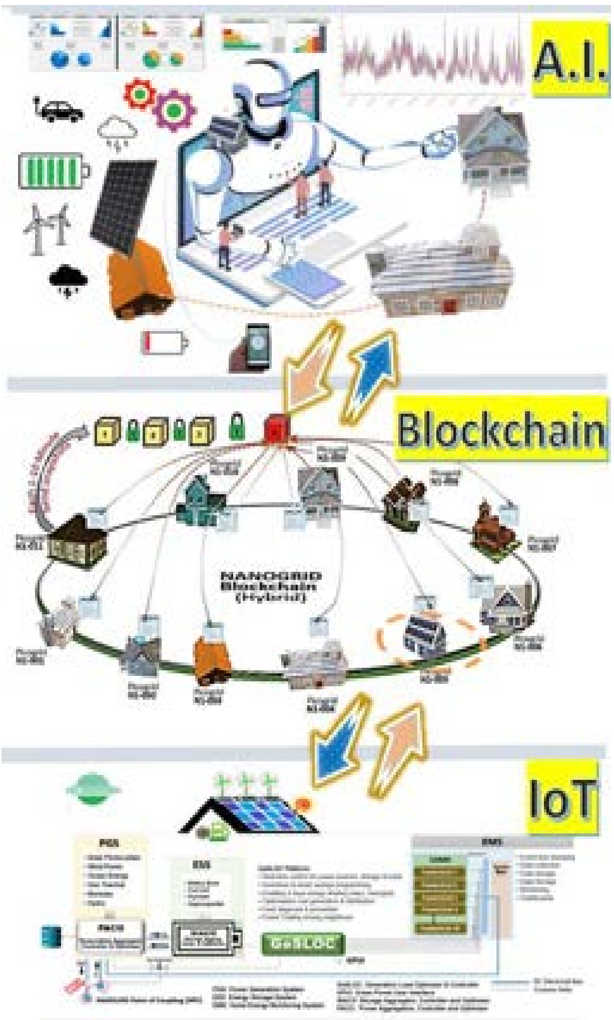


Figure 72: The BAIoT Systems - Overview

5.2.2.2 INTERNET OF THINGS - IOT

The BAIoT system relies on continuous data exchange among several power subsystems, whereas IoT provides the integration role, keeping the entire system running as a single unit. IoT agents perform data acquisition, monitoring, wrangling, sending and receiving data, taking corrective actions, and ensuring the network runs smoothly. IoT simplifies the integration among different systems., minimising communication complexities and offering many applications in the energy sector, e.g., energy efficiency, transmission and distribution, and demand-response [575].

As stated earlier, the BAIoT system is coupled with the ADCx systems, a small-scale autonomous DC power system - the *microgrids*, *Nanogrids,* and *picogrids*. Each entity counts on a Power Generation System (PGS), Energy Storage System (ESS), and Energy Monitoring System (EMS).

Several communication protocols can be used in a small-scale power environment depending on the application, feasibility, and specific local requirements. Solutions may deploy one of several communication protocols between sensors and signal aggregators or transmitting units, e.g., Bluetooth, Zigbee, Low6PAN, LoRaWAN, PLC, Wi-Fi, mobile phone network (3G, 4G, 5G), MQTT, and others.

Within the BAIoT system, IoT core tasks include: (a) interconnectivity and integration among several subsystems under a single framework, (b) automation, collection and process of the data from every subsystem, and (c) publishing results in a local database, (d) extracting and wrangling data and publish in a Blockchain, (e) act on the data after AI/ML analytics have been conducted and (f) send & receive data to all users (individuals, processes, an application, a device, or a machine).

ADCx system benefits from stratified consumption data for network efficiency and preventive reasons. Unlike the power grid, ADCx does not count on scalability, redundancy, or a robust backup system. The autonomy condition requires efficient mechanisms, so consumer data can be extracted, analysed, and applied to the system [576]. Best practices for energy management systems are automation and self-adjustable, to reach optimum power efficiency - this is where *femtogrids* play a vital role, making it unique among other systems.

All the technology, data, and functionalities are housed within the GeSLOC unit. BAIoT agents collect data from every power event and register them on a local database within the

GeSLOC unit. Later, another IoT agent sends snapshots automatically exported to the Blockchain. Stratified data enables advanced AI features such as implementing behavioural rules on a use category and behavioural levels. The sensors collect stratified data from each *femtogrid* and forward it to a micro-processing unit (gateway). A Smappee Infinity Energy Management System (EMS) [240] has been selected in this case.

There are many approaches to selecting the most suitable system and methodology for monitoring small-scale power plants. The choice involves several trade-offs involving security, complexities, timing, and costs. Load and power signature, authentication schemes, signal disaggregation, and Intrusive and Non-intrusive Load Monitoring (ILMs, NILM, respectively) are some approaches. The options for the processing, storage and user interface – the main trade-offs are costs, time to set up, maintenance, operations, accuracy, and degree of complexity. There is also the possibility of using individual current transformers or smart plugs and then building the APIs to display the information. Typical suppliers for EMS include Emporia Vue Smart Home [238], Powerpal [239], Smappee Infinity [240], TED Pro Home [241], Egauge [242], Efergy [243], Sense Energy Monitor [244], and many more.

The current sensors are placed in strategic locations, close to the appliance or inside the distribution panel, and then connected to a hub on the other end. Several hubs can be daisy-chained and connected to a microprocessor unit coupled with routing and LAN functionalities. The microprocessor unit can read the sensor measurements and send data to a router, which may publish the results in the localhost URL, send results to the cloud via the Internet, broadcast them via Wi-Fi, or re-transmit them to another location. Sensors collect data such as voltage, current, and active power from each usage category, power source and storage unit. Figure 73 shows the 8 CT (current transformer) sensors using non-intrusive methods from the Smappee Infinity solution package.

Figure 73: Eight Current Sensors from Smappee installed in the switching panel of a picogrid

All data collected by the EMS, ESS and PGS units

Figure 74: Each user sends a stratified data snapshot

are saved and stored in a local database using Node-RED or a similar development tool. Node-RED enables the connection of nodes, through browser-based visual programming, for building up a flow diagram, representing all the system components (e.g., sensors and actuators). It is a form of visual programing language (VPL) and a lightweight runtime environment that builds and executes the flows [236]. Node-RED is an event-driven, non-blocking model built on Node.JS, suitable to operate at the edge of the network on affordable computer hardware [577].

Message Queue Telemetry Transport (MQTT) is a Machine-to-Machine (M2M) connectivity protocol [578] that has been broadly used in IoT systems. It is a lightweight publish-subscribe model enabling efficient communication at the application layer. MQTT can run on Node-RED to secure the measurements from the sensors and automatically save them locally, in a defined format, data structure, and time interval. When raw data is captured by the sensors from several circuits and power sources, it is still blended and must be filtered, grouped, and prepared in a specific schema.

5.2.2.3 BLOCKCHAIN

BAIoT system deploys Blockchain technology with five primary purposes: (a) infrastructure for secure communications, (b) data access control, (c) payment rail and rewarding implementation schemes, (d) enable local economic development and *circular economy*, and (e) issuance of sustainability certification. Information continually flows between multiple systems, subsystems, and users. IoT initiates a group of activities (e.g., collecting data) and stores data results locally, and at determined intervals, snapshots are sent to the Blockchain, triggering other applications and features (Figure 74).

Enabling secure communication among untrusted parties without relying upon a central authority is a fundamental challenge in a distributed network [579, 580, 581] – and becomes a key enabler for the BAIoT-ADCx solution. Most of the existing security mechanisms in IoT are based on a centralised framework with registration and certification authority. However, this only makes sense when data governance is under a single entity. Proper management of security and privacy issues in a distributed network is critical, especially regarding how the system verifies and validates user requests. Under the BAIoT-ADCx environment, many householders (peers) must interact without disclosing privacy and identity. Static and on-transit private data become a continuous threat.

Data access control between AI and IoT agents is key to the BAIoT-ADCx models. For instance, data must be collected on established intervals from each load (or power source, storage system), aggregated, and stored locally under a dataset named for a given interval. There must be a specific IoT agent for that activity. Then, another agent should be able to access part of that data, process it (e.g., split, calculate the sum, encrypt) and send the result to designated channels in the Blockchain. On the other side, an AI agent may need to forecast the consumption (or power supply availability), considering the weather, temperature, and other stochastic variables.

A secure and reliable payment infrastructure is a foundational requirement for peer-to-peer (P2P) energy trading or bartering. User authentication, verification, and billing and payments must be in place. All metrics, such as current, voltage, power imported versus exported, financials, and timelines, must be registered in a reliable database. It should allow verification, auditing, data provenance (tracking), and ensure confidentiality and anti-tampering. Peer-to-peer (P2P) secured energy market architecture using a Blockchain platform has been proposed by several authors [582, 583, 584, 585, 586]. Once registered in a Blockchain's ledger, other agents can refer to it, conduct validation, provenance, issue smart contracts and follow up payments.

Energy trading is also a major advantage of the BAIoT-ADCx model. Beyond the financial component, it also enhances the entire system's resilience. The exchange of power resources helps compensate for power supply intermittence and load balancing. BAIoT strives to motivate users to trade their power excess or shortage via the DC bus. Beyond financial payment. Several other forms of compensation can be implemented, such as recognition, bonus for effective performance on energy savings, stock, discounts on local shops, free memberships, and other benefits.

Blockchain can provide a reliable and trustful payment rail infrastructure for network peers. Prosumers can exchange data, make decisions, agree on pre-established price mechanisms embedded in the consensus protocol, and finally send / import electricity among themselves. Once that is done, *smart contract*s are sent, and automated payments are made. Blockchain-IoT energy trading platforms have already been proposed and successfully implemented [213, 587, 211, 212] Seal-bid renewable energy certification trading in power systems using Blockchain technology.

Local Economic Development (LED) can greatly benefit from a Blockchain platform running within a community. Blockchain creates a new path for sustainable development by enabling business that focuses on eco-sustainability. It can help disseminate the idea that sustainable development is achievable on a small scale without relying on governmental actions. It is possible to become carbon neutral without relying on traditional polluted methods. Blockchain provides a reliable infrastructure, so local communities can prioritise local resources and become less reliant on third parties. By implementing liquid democracy in the consensus algorithm, communities can reach decisions much faster, come together and agree on the best approach to a problem. Several studies have been conducted considering the use of Blockchain to boost the local economy [588].

Circular economy is another extra advantage that could benefit from Blockchain technology. Resources can be tracked and re-used within a community, improving the chances of more environmentally friendly solutions. As it stands now, many companies exploit the recycling market niche; however, there is no visibility for the community on whether the benefits outweigh the liabilities. There must be tools and mechanisms to measure, register, track, and verify results over a period. Waste to Energy (WtE) or Energy-from-Waste (EfW) [589, 590, 591] are initiatives toward generating electricity and heat from the primary treatment of waste or the processing of waste into a fuel source. It is a form of energy recovery fully aligned with *circular economy*.

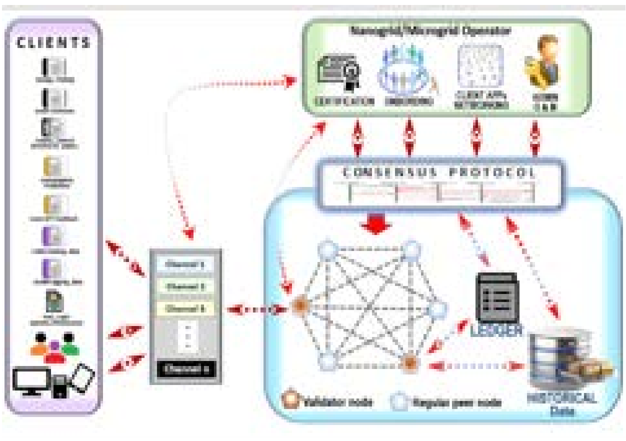
A certificate of sustainability can motivate users toward deploying environmentally friendly solutions. Reaching sustainability can be seen as a very high accomplishment within the community. New value-added services can ensure data provenance and enhance trust among untrusted parties. Blockchain can help to track events and create trust within a community. This is a key differential that the status cannot deliver. It brings added value to the property (or business). This is not a one-off certification used to greenwash products (or companies).

Sustainability indicators, customised targets, mechanisms to track the progress on reducing carbon footprint, and compliance could be embedded in the regulatory framework, reflected in the consensus protocol. Carbon footprint can be measured, monitored, verified, and results pushed into a Blockchain. Later, users may be able to request a sustainability certificate. Several studies propose Blockchain as part of the solution to measure and keep track of carbon footprint and carbon credit management [592, 593, 594]. Renewable energy certificates, compensation schemes favouring clean methods, and seal-bid energy auctions as trading mechanisms have also been explored in the literature [595].

Reducing emissions relies on optimising resources among users, which leads to an exchange of private and sensitive data. As mentioned, exchanging stratified consumption data is key to the BAIoT system for network efficiency, forecasting, and determining user behaviours (patterns). At determined time intervals (for instance, 10 minutes), each peer sends a snapshot containing a detailed data summary to the Blockchain, such as lights, space heating and cooling, food conservation, and so forth (Figure 75). Another agent extracts that data from each user, aggregates the entire content in a single file, and publishes it on the Blockchain. Once data is customised and structured, it can be then encrypted and distributed via the Blockchain. For trust and provenance purposes, results and hash digest are published in the ledger and can be visualised but not humanly interpretable. Only specific applications can decrypt, interpret, and send the results back to the Blockchain for data processing, analytics, and feedback.

Each user application (e.g., data acquisition, aggregation, cleaning, publishing, analytics) is assigned to distinct channels, where permission and restrictions rights are applicable. These processes provide client authentication and data privacy for some applications, assuring data integrity and provenance. For others, it makes it public, so collective action can be carried out as a group without the risk of being traced back to a single user. As the participants elect the management entity, tailor the consensus protocol and under what conditions the Blockchain should operate. These conditions may vary over time, lessons learned must be incorporated, bugs must be fixed, and new rules must be implemented. The

Figure 75: Blockchain channels for distinct applications



entity responsible for daily operations can propose software changes, but only the majority (51%) of voters can decide and agree on the consensus terms.

Depending on how the Blockchain technology is implemented, it may require some nodes to validate transactions before committing and registering data on the ledger (Figure 76). For instance, Hyperledger Fabric, an open-source modular Blockchain framework, uses permissioned voting-based consensus, the lottery-based consensus [139]. Hyperledger Fabric operates in a limited trust environment, which improves performance and provides low-latency finality. When most nodes validate a transaction, consensus is achieved, and the transaction can be validated. Since voting-based schemes require intense interaction among the peer, the greater the number of nodes, naturally, it takes more time to reach an agreement (consensus) on the state of the ledger. Several trade-offs must be considered such as timing factors, processing costs, security, anonymity, and more. Thus, the type of Blockchain selected becomes relevant since it impacts scalability, costs, user experience, performance and protection. Consensus in Hyperledger Fabric is achieved in three steps: Endorsement, Ordering, and Validation (Figure 76). According to [139], the endorsement is motivated by the policy (m out of n signatures) upon which participants endorse a transaction. The ordering phase obtains the endorsed transaction and decides on the order being committed to the records (ledger). For last, the validation process uses a block of ordered transactions and then, confirms the accuracy of the suggested block [139].

Several frameworks have been proposed for securing consensus in Blockchain-IoT for electricity applications [200, 201]. Blockchain applications for the electrical sector have become a hot topic over the past few years. Typical applications include peer-to-peer energy trading, network management, certification of CO_2 footprint, information security systems, and the release of energy crypto tokens [202, 203, 204, 205, 206, 207, 208, 209, 210].

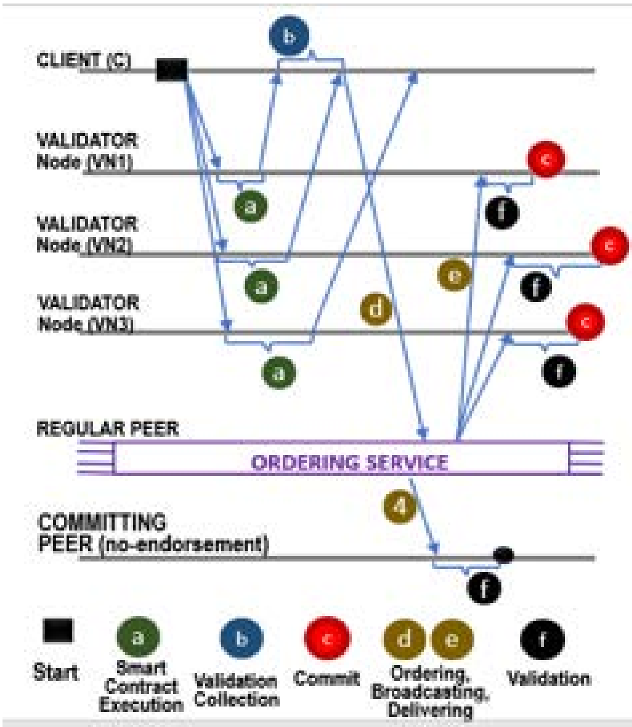


Figure 76: Blockchain validation - committing process

Apart from that, Blockchain models for the energy sector have been deployed in several startup ventures worldwide, LO3 Energy (USA), Power Ledger (Australia), Electrify (Singapore), just to mention a few. Around 2019, 140 Blockchain research projects and startups with potential applications on Blockchains for energy were identified [596].

Blockchain holds unique attributes that otherwise would be overly complex to solve by traditional technologies. In contrast to AC service providers who are not allowed to access private data from users, the BAIoT system can access, encrypt and exchange private data without disclosing identity and content. Through incentive mechanisms embedded in the consensus protocol, users may be motivated to make educated decisions when acquiring new goods and services and better control their GHG footprint.

5.2.2.4 Artificial Intelligence

Artificial Intelligence provides analytics to the BAIoT system by optimising network resources and supporting the users in making the best decisions towards autonomy and sustainability. Some of the high-profile tasks performed by AI agents include (a) forecasting load consumption, power supply, and energy storage, (b) estimating carbon footprint, (c) performing anomaly detection, (d) optimising consumption through building energy performance and savings, and (e) providing educational feedback to users.

Basic AI functionalities can be deployed using reactive machines to automate tasks and respond to known scenarios. Then, more sophisticated applications can be deployed using historical data saved in a local database, such as predictive and prescriptive analyses, fault detection, and real-time feedback to applications and users. On a more advanced stage, using a large amount of data, real-time AI agents can be trained to learn power supply and consumption patterns, understand the variables, and act proactively to maximise opportunities and minimise risks.

Forecasting supply and demand is critical to network management and solving the intermittence problem of variable renewable energy (VRE) sources, a major challenge for adopting renewable sources due to high integration costs [597]. Finding the optimum balance between production and demand becomes increasingly difficult in a decentralised network environment. Power stability control under dozens of variances, volatility of sources, weather conditions, failures, and demand-response requirements are permanent challenges. Sensors continually collect several types of data, creating large time-series datasets, which will serve as inputs to the AI agents. The skills gained increases energy supply (and consumption) efficiency. Many agents continually perform verification hand-shaking, seeking to optimally adapt the power supply systems to the current wind and solar power requirements [598].

The household is a valuable environment to educate users on the many aspects of GHG emissions. Users are misled to assume that climate change is only related to operational emissions and forget to account for the embedded emissions on objects, services, and buildings' embodied emissions. Heating and cooling applications are well-known major energy gutters. The number of air conditioner units is expected to triple by 2050. Air-conditioning energy consumption in the USA (in 2018) was equivalent to 20% of the world's consumption [599] - which is equivalent to entire China's demand for that same year. The warmer the planet gets, the greater the electricity demand. AI algorithms can support users in identifying thermal losses and improving performance and efficiency [600].

Smart building and industrial segments have benefited from AI technologies for decades to improve efficiency, reliability and automation. Energy consumption can be reduced through better control and demand response programs [601]. AI can outperform conventional systems by providing better management control, handling large amounts of data, cyber security, and improving energy efficiency [602]. AI is key to power systems to increase operational performance and user interaction.

AI algorithms can provide many features in a small-scale power system, such as fault diagnosis, anomaly detection, and network risk prevention. Leveraging power consumption, supply, and storage events and assisting end-users in detecting waste or fault can be cumbersome if done by conventional methods. AI can promote sustainable user behaviour, improve decision-making, and raise energy efficiency. AI agents can detect a minor component's problem before it escalates, thus acting preventively [603].

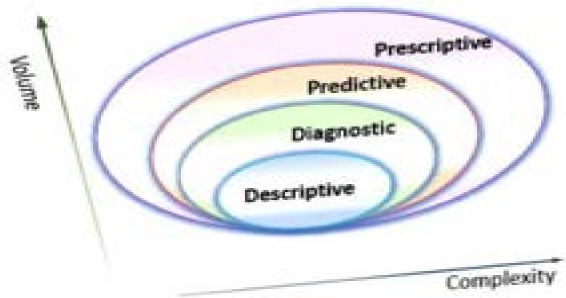


Figure 77: Data analytics types in BAIoT system

Gamification and serious games are tools that can help users to make better consumption decisions. These technologies can influence and trigger better consumption habits, save time, and ease the decision-making process by householders [561, 604]. Social computing and context-awareness technologies can impact consumers' behaviour and also improve overall systems efficiency. Better network management, faster fault diagnosis, lower energy losses, better monitoring system and more [605]. Together with Blockchain, AI can foster environmental governance and facilitate a transition to sustainability [606]. AI can support the user in achieving all the *17 sustainable development goals* (SDG) established by UN-GA (United Nations – General Assembly) [607].

AI agents are virtual assistants taking in all the information, comparing, analysing, modelling the data, and answering questions on the fly. Forecasting tasks may occur in pre-determined intervals or according to the requirements, and it may report results to the users in a suggestive or informative manner. For instance, if a user left the air conditioner switched on for 1 hour and motion detection sensors have not identified any physical activity in the house. Depending on how the system has been programmed and whether a similar event occurred in the past, the system could automatically respond to it by switching it off or sending an SMS message to the user. The number of user cases is unlimited, which could motivate users to reduce waste and emissions.

5.2.2.5 HOW BAIOT WORKS- METHODOLOGY

BAIoT agents continually capture data, run analytics to predict power loads, source supply, and energy storage, and provide user feedback. BAIoT uses specific agents to perform various tasks, prompting a series of actions to maximise benefits and minimise liabilities. All the BAIoT functionalities are installed in the GeSLOC unit (Generation, Storage, Load Optimisation & Controller), part of the ADCx model discussed in another study [574].

Figures 78 and 79 show an overview of how BAIoT works. IoT sensors and agents collect, transform, prepare, and transmit the encrypted data to the Blockchain. On the other side, another set of AI agents can decrypt, publish, and make it available to the AI agents. Then

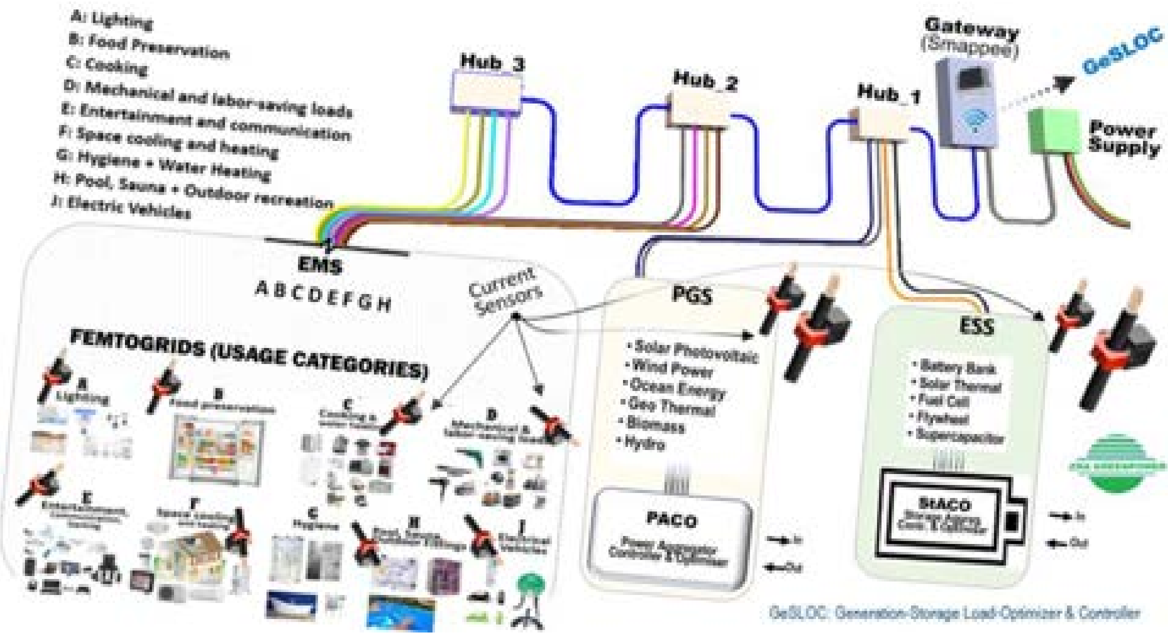
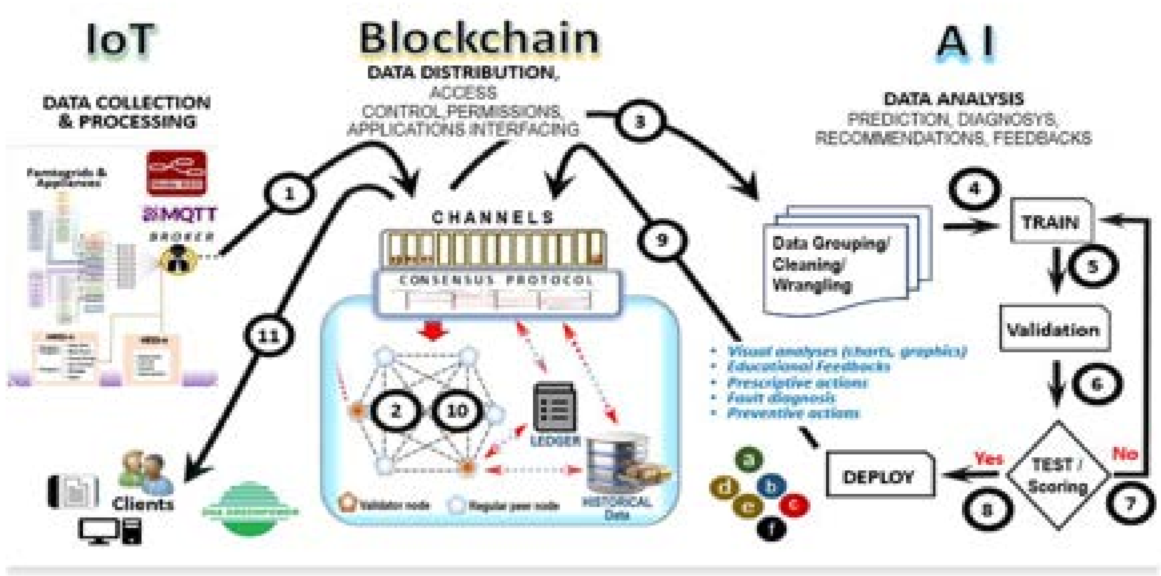


Figure 78: IoT system interconnecting EMS, PGS and ESS subsystems in a Picogrid

analytics take place (predictive, classification, fault diagnosis), patterns are learned, and feedback may be sent to the user through the Blockchain.

The BAIoT system expands GeSLOC capabilities by enabling an array of features to ADCx, such as system intelligence, user education, customised feedback, and emission footprint monitoring. The goals are to find an optimum balance between demand, storage, and power supply, ensure autonomy, and reach eco-sustainability.

Figure 79: Blockchain as a trustable data-exchange rail between IoT and AI



5.2.2.6 DATA ACQUISITION

Sensors collect data from every femtogrid (group of appliances under the same category, e.g., lights) and automatically register the results in a local database. Then, a local IoT agent accesses the raw data in the database, extracts the concerned portion of data (e.g., air-conditioners) within a time interval, and creates a temporary dataset. Data must be grouped by each usage category, according to each femtogrid. Next, another IoT agent runs transformations clean and wrangles the data under a specific scheme (Figure 80).

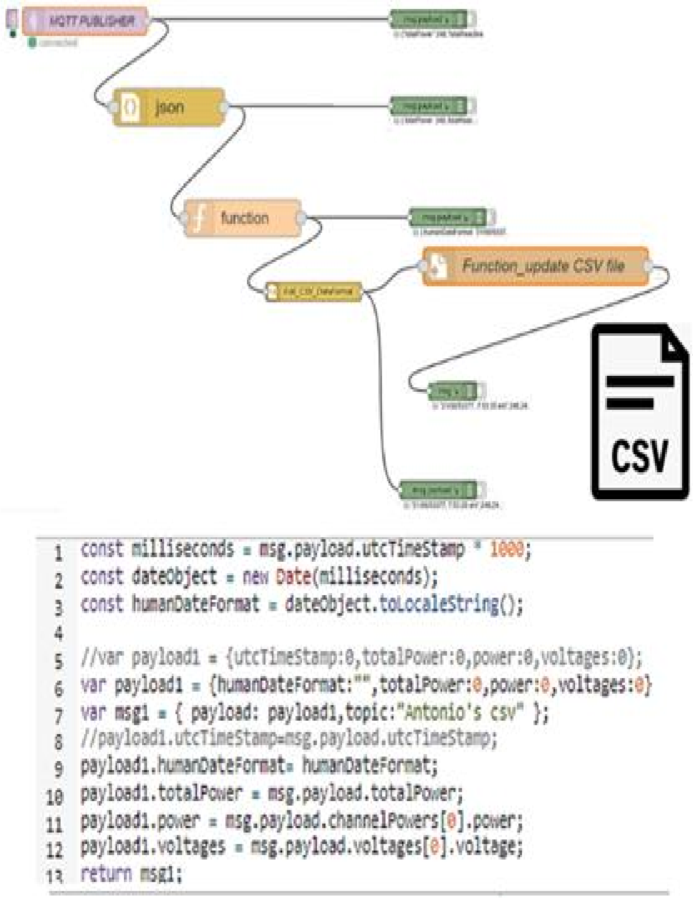


Figure 80: IoT data acquisition via Node-RED platform

For instance, a locally installed Node-RED system can access the data from each femtogrid, aggregate and save it in a single CSV file for each 15 minutes interval. A second IoT agent takes charge of encrypting, hashing, and sending the results to the *nanogrid's* Blockchain via a specific channel. At the other end, at the *nanogrid* side, a third agent embedded in the GeSLOC system, with the proper token access, extracts, read and decrypts the data from the Blockchain and saves it at the *nanogrid's* server. A fourth agent with Node-RED and MQTT capabilities must aggregate the data from each peer and publish it publicly in the Blockchain.

The gateway (from Smappee) continually receives raw data and pushes the results to the MQTT broker at the same pre-established intervals. The MQTT publisher sends the stratified consumer data to the MQTT broker, through the MQTT publisher, locally installed in a machine inside the building. At the other end, a second Node-RED agent, subscribed to the same channel, receives the data from all clients via the MQTT broker and sends it to the Blockchain.

The time interval may vary depending on the use case, *microgrids*, *nanogrids,* and *picogrids* (e.g., 1-second, 1-minute, 15-minutes). Taking a *picogrid,* for instance, the sensors collect 1-minute interval data from each group of appliances (*femtogrids*), from the Power Aggregator Controller & Optimizer (PACO) and the Storage Aggregator Controller & Optimiser (StACO) units, and also external data (e.g., weather) and then register on a local dataset (e.g., CSV format) for later use.

The gateway (Figure 10) is accountable for processing the data and interconnecting with the Internet (Wi-Fi & LAN connections). The power supply feeds the microprocessor and three other hubs with four connections. Each connection has a current sensor that extracts the signal from a power load, source supply or storage unit. In the case of a *picogrid*, each *femtogrid* represents a usage category. Nine use categories have been proposed in the ADCx over the BAIoT system: (a) lighting, (b) food preservation, (c) cooking and water heating, (d) labour-saving and mechanical tools, (e) education, communication, gaming(f) space cooling, and heating, (g) hygiene, (h) outdoor entertainment and (j) electric vehicles.

The system can improve accuracy and performance over time by systematically updating and comparing results with historical data. The goal is to find hidden patterns by selecting the best algorithms and predicting future outcomes. ML predictive algorithms can be defined as *"learning a target function (f) that best maps input variables (X) to an output variable (Y): Y = f (X)"* [608]. This is a basic functionality where BAIoT continually forecast new events (Y) given new information (X). BAIoT does not know what function (f) looks like until there is a large volume of data. The environment can be of *picogrids*, *nanogrids*, or *microgrids,* and conditions may vary in sizes, locations, and periods (e.g., seasons of the year, weekends). When BAIoT learns the pattern and selects the best algorithms, it can be re-used when a similar event is flagged. BAIoT keeps learning from new data. It may use previous patterns for faster decisions and later compare whether the decision was correct or not.

Although the BAIoT goal is to make as accurate predictions as possible within restricted timeline and computing power constraints, trade-offs do exist, as in any other computational system. Sometimes the high accuracy can compromise the performance of the overall system and leveraging these conditions are crucial to reaching a fine-tuning. BAIoT uses descriptive analyses to monitor the status of each subsystem, providing a comprehensive overview to the user. Virtual assistants can provide insights, and feedback, point out failures, or provide prescriptive actions. For each data interval, the incoming data is analysed, compared to historical data, and checked for flags, triggers, and pointers. The output may be in the form of datasets, text, sound, graphics, or plots for visualisation to the client (physical user or application).

Diagnostic analytics may provide insights into the reasons why a particular event is taking place. It could be a response to a fault, a shortage, or power leakage and may present possible root causes. It helps isolate relevant factors so corrective action can occur and automate automated decisions and tasks.

On the other hand, prescriptive analyses may recommend actions to be considered by the user based on past actions, strategies, and expected future outcomes. Prescriptive analyses deploy advanced analytical techniques to make specific recommendations – and be very computing-intensive. BAIoT may present strategies and alternatives to the user to mitigate a potential future problem by deploying prescriptive analytics

5.2.2.7 Data Preparation, Cleaning, Wrangling

Data cleaning (or cleansing) refers to detecting, correcting, and eliminating corrupt or incorrect data records from a dataset, which is crucial to analytics.

Within the BAIoT system, the process of data cleansing is achieved interactively, with data wrangling tools, cleansing, transformations, and formatting of the data under the desired structure. Batch processing can be performed through scripting, supported by the IoT system. IoT agents convert the incoming raw consumption data from sensors and aggregates by the Energy Management System (EMS) into a specific format, data types, and structure. Next, it transforms it into a cleaned format dataset and saves results in a local dataset, allowing Blockchain and machine learning mechanisms to process and further act on the data. This may include further merging, splitting, sorting, extracting, and creating a more convenient dataset, where other automated tools can interactively trigger other functions.

5.2.2.8 Data Splitting: Training, Validation, and Testing

The training dataset refers to the chunk of data used to represent the entire model – it will fit and train the model. The model intakes the training data and *learns* from it. The validation dataset "*provides an unbiased estimate of the skill of the final tuned model when comparing or selecting between final models*" [609]. The model becomes less biased as skills when new skills are continually integrated into the model. The validation set is also known as the development set (or '*dev set*') as it helps the development process of tuning the model hyperparameters. The test dataset is the portion of the dataset used that offers an unbiased assessment of a final model fit on the training dataset. The test dataset is used after the model is completely trained, tuned, and validated.

The test set is generally more mature data, containing experimented data including a wider range of classes, to be used in real production. The splitting rates between validation and test may vary according to the purpose and finality of the modelling (speed, accuracy, size). For instance, if the goal is to forecast one day ahead of electricity consumption, the training dataset may represent around 80% of the data, and the remainder, 20%, was split between validation (e.g., 18%) and test (e.g., 2%). The exact splitting rates may vary on a case-by-case basis.

In summary, the training dataset is used for conditioning (training) the model to learn a skill (e.g., a prediction function) and fit the parameters of the classifier/ regression/ clustering algorithms so that it can be used on unknown data. The (parameter) validation set uses a second and smaller amount of data to pick the best parameters (for tuning the model) to represent the model better. Lastly, the test set only assesses a fully trained and tuned model's performance, metrics, and measurements. It measures how effective the mode is in performing a certain task. The model score must be done on the test set (or the evaluation or "eval" set).

5.2.2.9 FEATURE SELECTION AND TARGET VARIABLE

Feature selection (or feature engineering) is finding what features (variables) contribute most to the prediction variable searched for, the target variable. Having irrelevant features in the data decreases accuracy, increases engine processing time, and forces the model to learn from irrelevant features. Feature engineering is a key aspect of any ML project since it impacts performance and processing time and can lead to ambiguous interpretations and results. Feature selection and data preparation are the initial and most important steps of any model design.

Key features in the BAIoT system are the stratified consumption data for each group of appliances, named femtogrids. There is a range of options for selecting the target variable in the BAIoT system, depending on the type of analysis, purpose, or reasons behind justifying the creation of an ML model. An analysis can be for exploratory, fault diagnosis, or prediction reasons. For instance, appliances such as air conditioners have different consumption profiles per year's season and might be a target variable in some situations. The amount of solar photovoltaic (PV) power generated could be another example. The carbon footprint for each facility (*picogrid*, *nanogrid*, or *microgrid*) can be an important target variable to bring tangibility to the GHG emissions problem.

Since the primary goals are to reach net-zero emissions and autonomy, forecasting becomes a key priority for the BAIoT system. Finding the total consumption for all appliance categories (femtogrids A through H) is key to BAIoT. ML models support the BAIoT system by predicting consumption one day ahead, e.g., increasing network efficiency and reliability and minimising shortage periods.

5.2.2.10 MODEL PARAMETERS AND HYPERPARAMETERS

A Machine Learning model can be described as a mathematical model with many parameters. While some parameters can learn from the dataset, others can be set manually or by using tools that will enhance the overall system performance to perform different tasks.

Model parameters refer to values that are automatically estimated by the ML model, from the training dataset, and are internal to the model. These numerical values are weights and coefficients that are learned when training the model. Model parameters consider how the target variable depends upon the predictor variable and whose values can be estimated from the training dataset. The ML model needs these parameters when performing a task, as they define the model's skill for a problem. They are the fitted parameters and internal to the model [610].

Conversely, model hyperparameters are external to the model, and can be set manually. The model hyperparameters enhance the ability of the model to make more accurate estimations for the model parameters. Hyperparameters are adjustable settings external to the model whose values cannot be estimated from the training dataset. The model must be tuned to find a model hyperparameter that returns the highest performance as evaluated by the validation set. In other words, the hyperparameters optimise the model performance by defining the default parameters applicable in all situations. Hyperparameter tuning solely depends upon the conduct of the algorithms when it is in the learning phase [611].

Typical examples of model hyperparameters are K in K-nearest neighbours, the learning rate for training a neural network, the penalty in Logistic Regression Classifier (e.g., L1 or L2 regularization) and the C and sigma hyperparameters for support vector machines [612]. Every type of problem has its specific set of hyperparameters, and to fit a machine learning model into different problems, its hyperparameters must be tuned. Selecting the best hyperparameter configuration of the models directly impacts its performance. Model parameters are like weights and coefficients seized from the data by the algorithm. Model parameters consider how the target variable depends upon the predictor variable. Hyperparameters solely depend upon the conduct of the algorithms when it is in the learning phase.

When tuning the hyperparameters, the data is divided into three parts: training, validation, and testing, so adjustments can be made in the default parameter to get the necessary accuracy to stop data leaks. The most common hyperparameter optimisation methods for machine learning are grid search, random search, Bayesian model-based optimisation and manual tuning. Hyperparameter tuning is the task of configuring the hyperparameter space for a set of values that will best represent the model design [613].

Models may include several hyperparameters – so, searching for the best combination of parameters can be treated as a search problem in itself. *GridSearchCV* and *RandomizedSearchCV* are the two most well-known techniques for Hyperparameter tuning [612].

Grid search is a method for hyperparameter tuning which defines a search space as a grid of hyperparameter values and assesses every point (position) in the grid [613]. For each value, the Grid Search creates a new model. In the end, every model that has been created is validated and rated, and the highest score with the best performance is taken. On each search, cross-validation is checked for evaluation, and scores are calculated.

The randomised search uses statistical distribution to inspect each hyperparameter. In some instances, some hyperparameters are not relatively important in a model, so not every combination must be evaluated as in a grid search. Bayesian hyperparameter can be used for complex optimisation problems. Global optimization is a difficult problem of searching for an input that results in the minimum or maximum cost of a given objective function [614].

It is customary to deploy "*naive optimization algorithms*" to tune hyperparameters such as the *GridSearchCV* or *RandomizedSearchCV* [615]. However, data scientists may choose a stochastic optimization algorithm, like the "*stochastic hill climbing*" algorithm. Manual hyperparameter optimisation can be computationally demanding since the objective function must be assessed multiple times to find the score for different hyperparameter sets. The goal is to find the hyperparameters that return the lowest possible error on the validation set – hoping that the results yielded can be generalized in the testing dataset. This implies the need of training the model, make predictions, and only then calculate the validation metrics. Manual optimisation can be impractical when there are multiple hyperparameters or more complex models such as deep neural networks or ensembles – that could easily last many hours or days to train and fit the model [615].

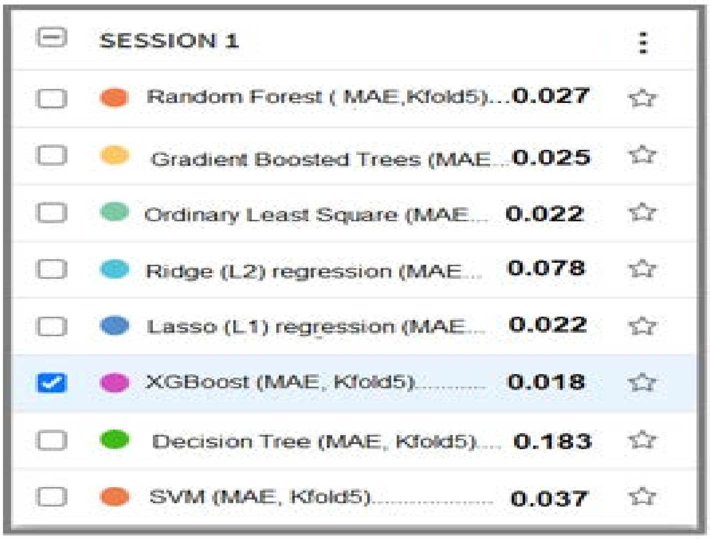


Figure 81: DSS output displaying XGBoost as winner model

5.2.2.11 Parameter Selection and Algorithms

Regression analysis is an approach for modelling the correlation between a dependent variable (the "target") and an independent variable (the "predictor"). There may exist one or many independent variables by using statistical methods. Several algorithms can be used for regression analyses, such as the Principal Component Regression - PCR, Stepwise Linear Regression - SLR, Partial Least Squares (Regression) – PLS, and Ordinary Least Squares (Regression) - OLS, [616]. The algorithm learns the correlation between the dependent variable, and how it changes when the independent variables are held fixed.

On BAIoT, the relationship between power requirement, the year's season, house size, dates, and time, is modelled using regression analysis. Based on established timelines, the BAIoT system must predict continuous values for power load requirements (or power generation).

In this case, the task is prediction, the inputs and outputs are numeric values, and speed is also important.

Typical predictive analysis algorithms used in BAIoT to train a model include Random Forest, XGBoost, support vector machine (SVM), Ordinary Least Square (OLS) and several others. Figure 81 shows the DSS training model results, including several algorithms and error metrics (MAE). In this case, XGBoost performed better when compared to Gradient Boost, Ordinary Least Square, and others. In this instance, the goal was to predict power demand and energy supply one day ahead for a picogrid.

Random Forest (RF) Ensemble is a prevalent algorithm in supervised machine learning models, capable of classification and regression tasks. The variance in decision trees can be reduced by using training on different samples of the dataset. It reduces the overall variance of the classifies. Alternatively, random feature subsets can be specified and combined. For instance, if there are 20 features, random forests may only use a limited number of those features in each model, (e.g., 5) [617]. For the final decision, the RF classifier gathers all the decisions from each tree; therefore, RF can reach superior generalization [618].

Extreme Gradient Boosting (XGBoost) is a well know algorithm applied in machine learning, an implementation out of the Gradient Boosting method, which uses more precise calculations to find the best tree pattern [619]. It utilizes special techniques to improve performance, especially when using structured data, such as second partial derivatives of the loss function. In doing so, it collects more data about the path of gradients, therefore reducing the loss function. Whereas traditional gradient boosting deploys the loss function of the base model as a substitute for minimising errors, XGBoost uses a second-order derivative as an approximation [619]. Also, it performs enhanced regularisation (L1 and L2), improving the generalisation, saving computational resources, enabling parallel computing, and saving time.

Supporting Vector Machine (SVM) is a popular machine learning algorithm used in supervised learning methods for predictive and classification methods. In practice, the SVM algorithm is implemented using a kernel [620]. It outputs each data point as a point in n-dimensional space, where n = the number of features. For instance, when two features are selected (e.g., height and weight), it first plots the two variables in a two-dimensions, with 2 coordinates, known as support vectors.

5.2.2.12 ERRORS METRICS

Error metrics selection is required during optimisation and measuring the model's overall performance. Once the type of problem is clear, the metric selection takes place. When the task refers to prediction, the inputs and outputs are numeric values so that the metrics will measure performance between inputs & outputs, e.g., the likelihood of power output requirement 1-day ahead. The results will be compared to unknown data and measured in terms of errors. The following are some of the popular metrics in regression analyses:

Mean Squared Error (MSE) measures the median sum of the square of the difference between the actual value and the forecasted value for all data points. Since it squares the value, it eliminates negative values. It quantifies the total of errors in statistical models.

$$\boldsymbol{MSE} = \frac{1}{n}\sum \boldsymbol{e_t}^2\ ,\ where\ \boldsymbol{e_t} = Original_t - Predicted_t$$

The impact of errors grows by quadrature from the original value, making it very sensitive to outliers. The lower the MSE, the more accurate the prediction becomes.

Mean Absolute Error (MAE) calculates the arithmetic average magnitude of the errors between paired observations, disregarding the direction (positive or negative). MAE represents the average of the absolute differences over the test sample between prediction and observations – with equal weight for each difference.

$$\boldsymbol{MAE} = \frac{1}{n}\sum |\boldsymbol{e_t}|,\ where\ \boldsymbol{e_t} = Original_t - Predicted_t$$

MAE is an alternative to the outlier-sensitive MSE. Because it takes the absolute value of the errors, the effect of one outlier will not radically impact the results compared to MSE or RMSE.

Root Mean Square Error (RMSE) is another popular method for analysing the relationship between one or more predictors and a response variable [621]. It calculates the square root of the average of squared differences between a prediction and an observation. In other words, it calculates the squared standard deviation of the residuals, between prediction and original value, highly used in regression problems. It assumes a normal distribution as if there were no error biases. As it deploys the *'square root'*, it automatically increases the magnitude of error deviations. In turn, it inhibits cancelling the positive and negative error values.

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum_{1=1}^{N}(predicted_t - original_t)^2}{n}}$$

RMSE avoids the inconvenience of absolute error values, highly undesirable in arithmetical computations. When the number of samples is high, recreating the error distribution using

RMSE is consistent. However, since RMSE is highly sensitive to outlier values – it implies that outliers must be removed before applying RMSE. Depending on dataset sizes and timing, that may become an extra challenge. The lower the RMSE result, the better a given model can "fit" a model. Compared to MAE, RMSE gives higher weightage; however, it punishes large errors.

Multiple error metrics can be used simultaneously depending on what are the objectives. Depending on the use case, some methods may better fit a situation. For instance, if MSE was firstly selected and metrics were high, that provided a valuable indication of the presence of outliers. So, MAE and RMSE were used and compared.

5.2.2.13 LAG FUNCTION

Lag refers to a time delay and the amount of data history the model can use when running predictive analytics. Lead corresponds to the period between the last data point the model can use to predict and the first data point the model predicts. Both lag and lead are positional functions expressed in time units (e.g., minutes, hours, days).

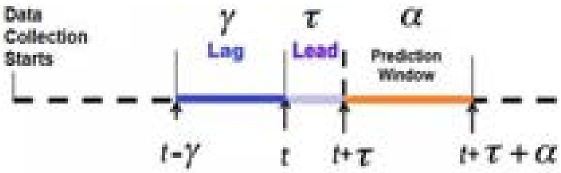


Figure 82: Lag and Lead concepts in a time-series analysis

The lag, or window sliding function, is one of the techniques for running computation across different time observation periods. It is an attempt to increase model performance. In time series, the lag() function allows access to values stored in adjacent roles. The BAIoT system uses this technique to relate the values of a variable in the current observation to the value of the same or another variable in the previous observation (e.g., last hour, last day, last month).

Figure 83: Snippet of the DSS recipe for lag () function

Autocorrelation determines the relationship between a given time series and the lagged version of that time series over successive periods, in terms of similarity. Although it can similar to calculating the correlation between two different variables, for autocorrelation, the correlation is calculated between two versions X_t and X_{t-k} of the same time series.

$$r_k = \frac{\sum_{i=1}^{n-k} (Y_i - \bar{Y})(y_{i+k} - \bar{Y})}{\sum_{i=1}^{n-k} (Y_i - \bar{Y})^2}$$

The Lag () syntax is:

LAG (expression [,offset[,default_value]]) OVER(order by columns).

Figure 13 depicts a snippet of the recipe used in Data Science Studio (DSS) for the BAIoT lag function calculation.

Figure 83 shows the concept of lag function for a prediction problem where a model tries to predict t + τ and t + τ + α using data points between t - γ and t.

5.2.2.14 DATA BINNING, ERROR BIN, BUCKETING

Data binning, errors bin, discrete binning, or data bucketing refer to data-processing techniques aiming to reduce the effects of minor observation errors. It helps the visualisation by classifying the results under specific thresholds (e.g., percentage). The goal is to categorise the number of outputs, create error ranges, and facilitate interpretation. That can highly help the user better contextualise and interpret the problem. Depending on the deployed stage, it also reduces processing time and complexity. The original data points sitting under a given small interval, a bucket (or bin), are substituted by a standard value representing that interval, usually the central point. It is a form of error quantisation to streamline interpretations.

This study deployed the error bins technique after the model had been fully trained and tuned on the evaluation datasets. Figure 84 shows the error percentage bins for predicting the average Absolute Error Percentage Error (APE) for total appliances in categories A through G (as detailed in section 5.1.3.4).

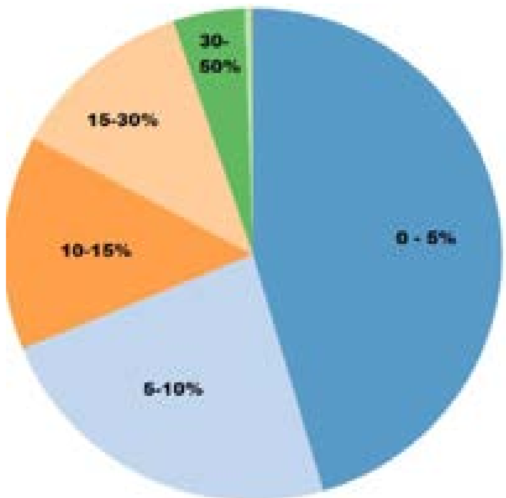


Figure 84: Error Bins for Absolute

5.2.3 MAIN CONTRIBUTIONS OF THIS STUDY

The importance of this study includes:

i) Clarifying that reducing global emissions requires enabling tools, techniques, and infrastructure so users can educate themselves, change behaviours, and make consistent pro-environmental choices;

ii) Establishing a pathway for users to take accountability for their direct and indirect emissions (e.g., embedded on goods and objects or embodied on buildings);

iii) Showing that instead of using technology to stimulate more sales and acquisitions (like vendors and advertisers do), it can be used in the opposite direction to shield the user against unbounded purchases and consumption.

iv) Demonstrating that Blockchain, AI, and IoT can work together to support and guide users towards their sustainability journey;

v) Reinforcing the notion that there is no solution for global emissions without having an infrastructure away from the AC grid and the current stakeholders in the electricity industry;

vi) Illuminating that only a global solution that accounts for all the root causes together can solve the global emission problem;

vii) Presenting a logical structure to support users to gain independence from a system that delivers "cheap" electricity at the expense of the environment;

viii) Shedding light on the importance of artificial intelligence and analytics to support users to reach sustainability and avoid the rebound effect;

ix) Enlighting about the BAIoT capabilities in supporting Local economy development (LED) and *circular economy;*

x) Enabling the exchange of private and sensitive data among users (which would be unattainable for the existing system (AC power grid)

5.2.4 CONCLUSION & FUTURE WORK

The BAIoT system brings a new rationale for using technology to support small-scale and decentralised power grids. Competing with the existing AC electrical system built on a "*polluted and cheap*" mindset is a very challenging undertaking, which justifies this study. BAIoT enables a paradigm shift for using technology to help people and the planet - not supporting something else that later will contribute to depleting the planet. Blockchain, IoT, and AI technologies have been far more used for commercial and financial gains without due care to the environment. However, in this study, Blockchain creates trusted communication channels and payment rail so subsystems from non-trusted parties can communicate and exchange information safely. IoT automatically collects data from appliances, power supply, and energy storage systems, perform data transformations, and integrates all the subsystems under a single platform. AI supports individuals, households, and organisations to make better decisions. AI agents can track hundreds of events, anticipate scenarios, run diagnoses, and send feedback, so users can raise awareness, understand the options, and reach net-zero. The existing AC system cannot achieve these features since it deals with sensitive data and user privacy. The BAIoT system brings together several concepts and details on how to integrate the many components. It is complex since it deals with electricity and a wide range of software and hardware that enables automation, data security, processing, optimisation, and intelligence. BAIoT offers near real-time analytics, enabling tailored feedback to the individual so educated choices can be made towards supporting the environment. In the pursuit to reach net-zero locally, BAIoT can potentially enable the introduction of rewards, motivational mechanisms, and sustainability certificates.

This study is followed by a framework (by the same authors) presenting an underlying structure to support the electricity industry in combating global emissions. Also, future work should include:

- Listing all the agents for AI and IoT, specifying their requirements and their exact functionalities;
- Determine the Blockchain features, protocols, platform, consensus, and algorithms for verification, ordering, and solving the double-spending problem;
- Run simulations and test each feature for each agent;
- Assemble the whole components under a single BAIoT platform and ensure the end-to-end model works as expected;

5.3 BAIoTAG FRAMEWORK: ENABLING A FASTER TRANSITION TO SUSTAINABILITY

Abstract:

Electricity is the major contributor to global emissions and a major nodal point for solving climate change since it powers every other industry. As a result of a monopoly scheme and the absence of laws for protecting the environment, the A.C. grid delivers low prices and high-quality Energy at the expense of the environment and future generations. Consumers have no options for a cleaner power system, no tools, and no hope that a credible plan will soon emerge. This paper introduces the BAIoTAG framework, which addresses roadblocks and root causes of global emissions. It presents the 12 foundational principles to guide individuals and communities toward a pro-environmental solution, moving away from the status quo. It boldly assumes the limitations, conflict of interests, and the inability of current power brokers to reduce global emissions. It addresses the monopoly problem, the need for new infrastructure, and the assortment of tools required to quantify, mitigate, and raise awareness, so users can become motivated to reach sustainability. The BAIoTAG framework envelops the ADCx and BAIoT models, two previous studies complementing each other, presented by the same authors. The BAIoTAG is unique in creating the necessary environment to overcome the emissions problem from the electrical sector. It provides the foundation for the ADCx and BAIoT models while allowing the inclusion of theoretical games to further motivate users towards reaching echo sustainability. To the authors' best knowledge, this is the first time a framework is explicitly presented to solve the global emissions problem, advocating for new infrastructure, and supported by a combination of technologies.

Keywords: BAIoTAG, Blockchain, IoT, AI, BAIoT, ADCx

5.3.1 INTRODUCTION

Development in science, technology, and economic development have highly influenced population growth and human behaviour. The Industrial Revolution led to the intensive use of electricity in houses, factories, and businesses and triggered transportation, machinery, and communications development. Food production increased substantially, and so public health and human life expectancy. From one billion inhabitants in the early 1800s, the population reached seven billion in the year 2000 and now is poised to reach ten billion by 2055. The correlation between technology and population growth is noticeable and indisputable [622]. So is the correlation to environmental degradation [370]. Technology brings benefits and liabilities, and most institutions benefit from it without paying attention to the consequences (Figure 85).

Figure 85: Landfill site of village of Pallakkadu, Sri Lanka
Source: The Guardian, Achala Pussala /AP [370]

Changes in the investment capital in the mid-19th century led the government to outsource some of the estate responsibilities to the private sector. Modern corporate law, joint-stock companies, limited liability, personhood and perpetuation all gave rise to unrestrained production [623, 624], protecting the investors and failing to protect the environment. The success of corporations today relies almost exclusively on their capacity to produce, market, and sell their products and services. There are neither rewards for reducing production nor avoiding environmental impacts.

The transitioning of responsibilities from the state to the private sector impacted the educational sector, especially the higher education segment. For the most part, it became a branch of business, a spin-off from the division of labour, where institutions create tailored products in specialised fields, such as engineering, law, medicine, and many others. Specialisation improved the short-term economics and enabled newer technologies, increasing financial gains in a shorter time; conversely, it has become a threat to the environment and future generations.

The more specialised the world becomes, the greater the difficulty in addressing multi-disciplinary problems, such as global GHG emissions. A problem that is affected so many distinctive domains that it makes it extremely challenging to stream it down to the real root causes. Science, business, politics, education, technology, and human behaviour – all correlate to global emissions. Thus, reversing the climate problem requires multi-disciplinary skills, not single-minded specialists.

Thousands of educational institutions have emerged globally, aligned with regional policies for regional development. They provide training and tools for the future workforce to support governmental and industrial needs. Once specialised in a field, end-to-end visibility is lost. On the hunt to find "innovative" solutions capable of reaching the masses faster, anytime, anywhere, higher education has become a test bed for startups and business incubators. From an environmental perspective, schools merely offer a product in exchange for rewards. Once the training is delivered, the school have no control over what happens to the student – nor the consequence to the environment.

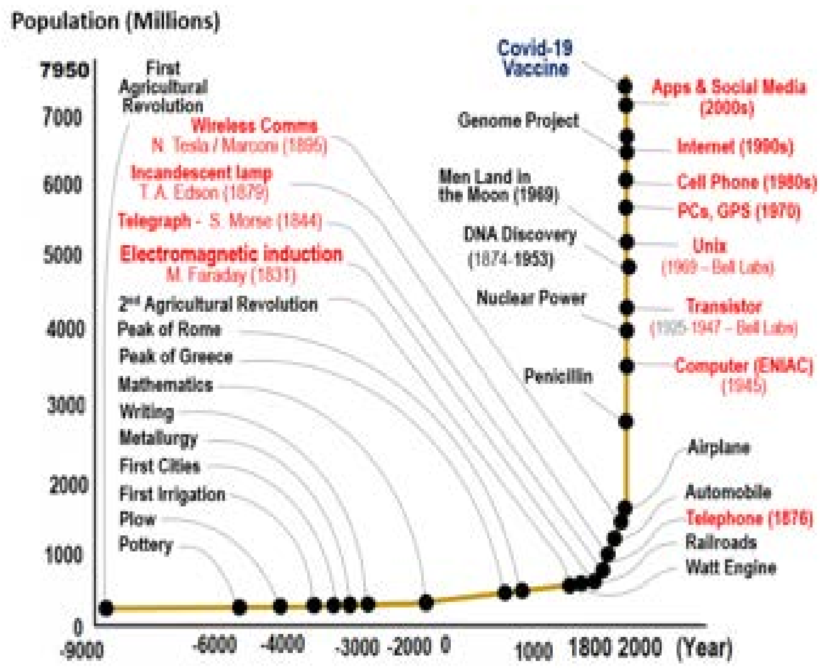


Figure 86: Population growth and major technological events

Large transnational corporations control most of the global capital investment in the 21st century [573] and are present in every strategic sector: Energy, technology, finance, industrial, and service utility. The influencing power capacity of these institutions on policy-makers and decision-makers is pervasive and hardly noticeable. Through the daily media, apps, and ads, these institutions can confuse the public and keep a low environmental awareness.

The mutual dependence between government and large corporations compromised their autonomy from the governments in spearheading new laws to protect the environment. As the administration requires more funds (taxes, social security), it has no option but to support local corporations to increase productivity and exports. Global exporting is key for developed economies; however, the higher the exports, the higher the interdependencies among the nations. The vicious cycle in exports creates a strong bond between importers and exporters. Thus, no single country can be accountable for its environmental problems because they belong to the same network.

Unrestrained production leads to uncontrolled emissions since the role of looking after the environment has been abandoned. Billions of devices, vehicles, and appliances hit the market each year, faster and cheaper. The side effects are more GHG gases, forest clearance, droughts, and global warming. In turn, threats to health, livelihoods, food security, water supply, and human security are increased in the same proportion [625].

Development in science, technology, and economic development have highly influenced population growth and human behaviour. The Industrial Revolution led to the intensive use of electricity in houses, factories, and businesses and triggered transportation, machinery, and communications development. Food production increased substantially, and so public health and human life expectancy. From one billion inhabitants in the early 1800s, the population reached seven billion in the year 2000 and now is poised to reach ten billion by 2055. The correlation between technology and population growth is noticeable and indisputable [622]. So is the correlation to environmental degradation [370].

Changes in the investment capital in the mid-19th century led the government to outsource some of the estate responsibilities to the private sector. Modern corporate law, joint-stock companies, limited liability, personhood and perpetuation all gave rise to unrestrained production [624, 623], protecting the investors and failing to protect the environment. The success of corporations today relies almost exclusively on their capacity to produce, market, and sell their products and services. There are neither rewards for reducing production nor avoiding environmental impacts.

5.3.2 Can Governments Act Together and Cut Emissions on a Global Scale?

Every year nations send their top representatives to renew pledges on global emission mitigation tactics during the Conference of the Parties (COPs). Most spent their entire lives within a controlled environment, making it challenging for the public to conceive any positive outcome. Inevitably, questions have been raised about whether COPs have been merely used as a tactic for perpetuating the status quo.

Mauna Loa observatory (Hawaii, USA) reports that emissions have been rising steadily for the last 60 years (at least) [626, 405]. The political and business components of the COPs are noticeable. Financial contributions to the U.N. are made voluntarily [627, 628], whereas top contributors are among the same nations that historically have been the most polluted [389].

The energy sector is a primary beneficiary of emissions, as they profit from deploying unclean methods, including fossil fuel exploration and supply, electricity producers, grid operators, and utilities. Secondary beneficiaries include every entity that relies on supplying energy sources to conduct their business. Any institution participating in the industrial or business chain is a co-beneficiary of GHG emissions. Technology, building, education, software development, consulting firms, financers, or any industrial domain that derived profits from the existing socio-political-economic model, have necessarily benefited from global emissions.

As part of a cultural and educational process that has been propagated for centuries, founded on the myth of progress [7], people have been induced to improve themselves, and new acquisition of goods and services (labour) became a symbol of power and social achievements. People were induced to purchase products and consume electricity without any restrictions. People do not realise that it takes fossil fuel to produce electricity and plastic, rubber or transport food from the farm to the supermarket. Since every industry relies on electricity, power suppliers have become gigantic institutions. Millions of intermediaries emerged to support productivity and stimulate consumption. Most acquisitions result from aggressive marketing stimulation and are no longer about fulfilling individuals' essential needs.

Current power brokers (government, large corporations, financiers) cannot intervene to solve the emission problem since they are the most interested parties. So, power brokers continue passing a public message of hope, like the transition to renewables or the carbon market, which have been proven fruitless in solving the emissions problem.

When a country pollutes, it affects the entire planet, implying that global GHG emissions cannot be addressed domestically, in isolation. The gap between reducing territorial emissions and reaching global sustainability is gigantic. Whereas there is no global authority to impose rules at the stratosphere level, it is very unlike developed countries that will create conflicting rules for their local organisations.

Measuring and reporting domestic GHG emission results is another hurdle to overcome. Without a global consensus on the methodology, including measurement, report and verification, and law enforcement, it leads to stakeholders make predictions and release figures based on ambiguous guidelines. The Measurement, Reporting and Verification (MRV) initiative from Paris Agreement [629] raises the importance of the process but does not provide a solution [630, 631]. All data has assumptions, boundary limits, and partial relevance. There is no shortage of creativity when juggling numbers and graphics.

The complexities brought by the global value chain, logistics, reliance on third parties, and international suppliers make a top-down solution exceptionally unfeasible. Unless a country withdraws from civilisation, with no imports nor exports, it could never claim sustainability. Sustainability can only be achieved as a global effort, never locally. Countries with strong financial international ties, exporting and importing goods and services regularly, can never claim 'net-zero" conditions on their own.

Based on all the above, it can be concluded that:

- If decision-makers had the power (not willingness) to change the laws and regulations and impose strict penalties against releasing emissions, that would have already happened long ago
- By keeping the same environment, same stakeholders, legislation, motivations, and business models make it highly likely that the current situation will only worsen.
- Even in the hypothesis that some countries announce their success in achieving net-zero conditions through renewable sources, the positive impact on a global scale is likely to be minimal.
- With the expected population growth, the likelihood of improvements in social conditions, and the natural increase in consumption rates, it is highly likely that the bulk of global GHG emissions will keep rising.
- Poor environmental education leads to public unawareness of the global emissions threat, which creates extra roadblocks to combating global emissions;

In the next section, this study presents the BAIoTAG framework, outlining the guidelines and principles to support individuals and organisations in the transition to sustainability.

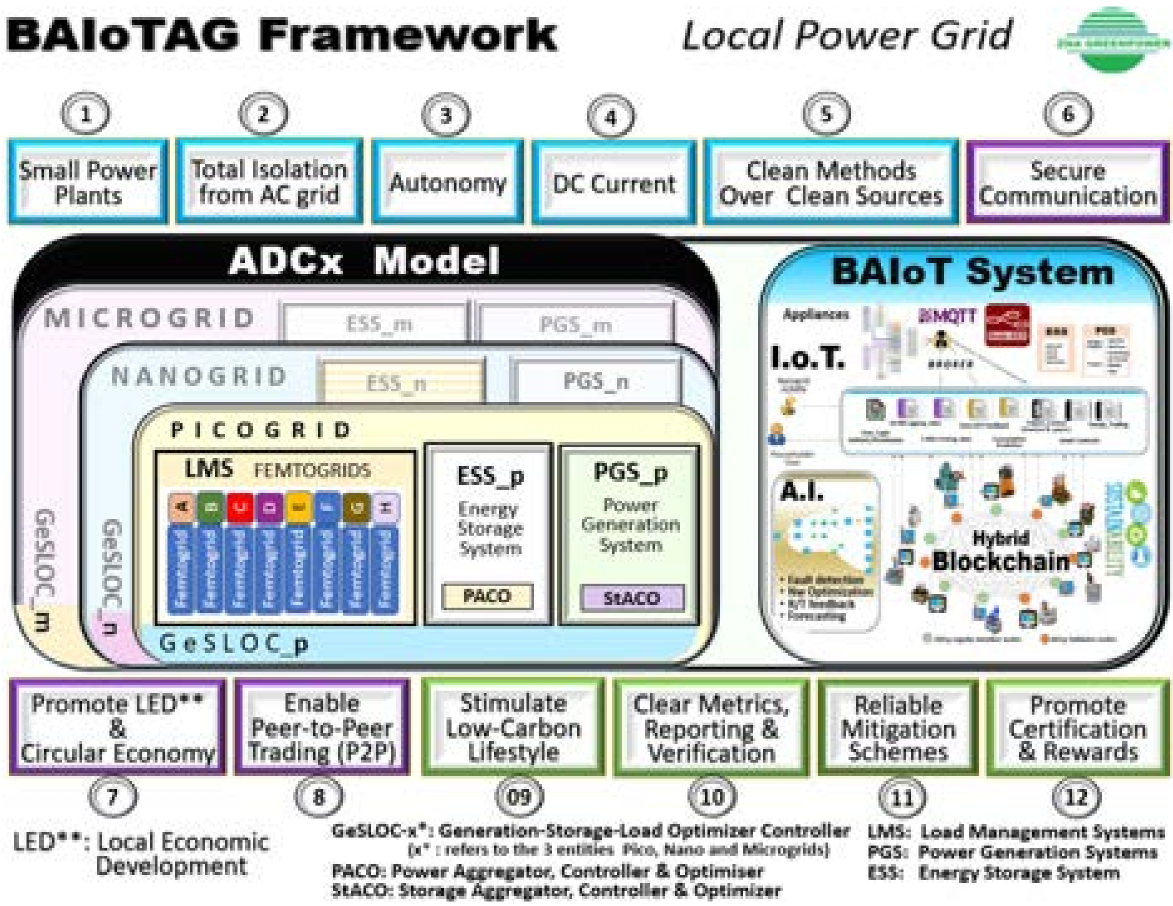


Figure 87: BAIoTAG Framework: The 12 foundational principles for a cleaner power grid

BAIoTAG provides a new pathway to reduce emissions spearheaded by the community, creating an alternative where there was none before.

5.3.3 THE 12 PRINCIPLES FOR THE BAIOTAG FRAMEWORK

Presenting a solution for the global GHG emission problem touches several domains, revealing values that have been ingrained in society for centuries and have now become roadblocks. It touches human behaviour, legislation, technology, economy, physical science, education, and every single entity with a financial bias. The ability to cross territorial boundaries, minimum dependence on existing power brokers, and inducing new values to society without directly conflicting with the existing ones are all parts of the puzzle. Besides, it must be simple, replicable, and offer unique advantages unachievable by the status quo.

The BAIoTAG framework creates the ideal environment for a new power system to blossom. The key goal is to enable users to realise their importance towards sustainability. The framework accounts for the infrastructure, motivation mechanisms, and tools so the whole system can work together. To that end, the framework is founded on 12 principles as follows:

(1) Small size power plants
(2) Total isolation from the A.C. grid
(3) Autonomy (whenever possible)
(4) Direct Current (exclusively)
(5) Cleaner methods over clean sources
(6) Secure communication
(7) Local Economic Development & *circular economy*
(8) Peer-to-peer (P2P) energy trading (or bartering)
(9) Rationalise consumption through incentives
(10) GHG automatic calculation
(11) Emission Mitigation Schemes
(12) Eco-sustainability certificates

PRINCIPLE 1: SMALL-SCALE POWER PLANTS

Being small-scale is an antidote against monopolies and oligopolies, a major root cause of global emissions. If only a few institutions with strong financial biases are allowed to explore a market niche with essential products and services, the entire society becomes a hostage from these institutions. Because when emissions are released, the entire atmosphere is affected, not only the location where they were originally emitted.

Small-scale power is a clear-cut axiom with a predictable outcome and many proven results. As the energy sector (fossil fuel and electricity industries) grew extra-large, it increased bargaining power and attracted a long chain of supporters (secondary service providers). Besides eliminating competition, monopoly (or oligopoly) also reduces the participation of the community. Monopoly (and oligopoly) undermines democracy as institutional interests are prioritised. They can lobby, pay for the media, manipulate vulnerable stakeholders, and influence policymakers with enough resources. Individuals (and smaller organisations) have no alternative other than using the existing electricity system, which has become the key source of global emissions.

Funding, subsidies, and incentives are negotiated without weighting long-term consequences to the environment. End-to-end visibility is lost, and real facts become blurry. The outcome is the same as the community has no say in it, sharing similarities with countries where there is no democracy.

The energy sector has special traits not shared by any other business segment. A group of 100 corporations in fossil fuel production are responsible for 71% of the global emissions [451]; Of that, 59 are state-owned companies. For the most part, large corporations in the energy sector can generate emissions freely, as long it delivers low prices for fossil fuel and electricity. Since there are no rivals and they are legally sound, it is up to them to choose the lowest cost for the transformation methods. Governments, investors, and large corporations are far more concerned with low energy prices than low emissions. To further confuse the public, the media industry broadcast a questionable solution, where renewables and the carbon market become the medicine for fixing climate change. On the downside, it has been helping to perpetuate the problem and providing a misleading hope to the public. Many barriers prevent new players in the electrical sector, including legal, technical, and financial constraints. Although some countries have opened for competition, it is unfeasible to compete with unclean methods and still be competitive.

Analysing government agencies or power utility websites will conclude that governments are on the fast track towards sustainability. Conversely, global emissions keep rising steadily [385, 336, 491]. The energy sector (electricity, heat, and transportation) accounts for over 70% of global emissions [422, 632]. Stakeholders emphasise their virtues on power quality and availability and hide the negative effects caused to the environment, which partially help to explain why GHG emissions have been rising steadily for many decades.

Deploying large, centralised power plants with unclean methods enables lower prices and solves a punctual political problem. However, it creates much greater difficulty in the long run. With the concentration of power and the strong bond with regulatory bodies and media, there is no expectation that the electricity industry can create an effective solution to lower emissions.

Political parties in developed economies average 4-8 years in power, so the emission problem is always rolled over to the next successor power broker. The impact of GHG emissions has been reported for over a century [72, 73]; however, there is no continuity, no long-term commitment toward protecting the environment, only new pledges around the elections period. This is a systemic problem, copied and replicated across the globe. Leaders are judged upon their abilities to boost the economy, increase GDP, and provide benefits during their time in office, not by their ability to reduce emissions

The electricity industry is heavily trapped between legislation and regulation guidelines, the concentration of power from the energy sector stakeholders, and surrounded by politics and lobby. A new design mindset must be built, including small power plants, with many service providers competing for lower emissions rates, not targetting only lower prices. Local and sustainable communities can be formed without a monopoly or long transmission lines to reduce power losses.

PRINCIPLE 2: TOTAL ISOLATION FROM A.C. GRID

The A.C. grid prioritises scalability, large coverage areas, and a centralised design model coupled with minimal costs for transformation methods. Given that two antagonistic design models cannot co-exist under a single structure for technical reasons and added legal and economic constraints, competition is automatically eliminated.

If a new prospect exists for a clean power grid, new infrastructure must be in place, totally isolated from the A.C. grid. Given the existing regulation, it becomes technically and economically inviable to share the same infrastructure with the existing power grid. Therefore, full separation of concerns is vital for an alternative system to compete with the status quo. As the legislation makes the A.C. power system exclusive, it protects the status quo and interests of the existing stakeholders. Besides, co-existence would imply unnecessary conversions, power control complexities, safety risks, extra costs and the perpetuation of the emissions problem.

Thus, the strategy is to build a new system that avoids technical and regulatory constraints embedded in the existing (biased) codes. Being isolated from the A.C. grid becomes a pre-condition for becoming competitive. On the pro side, it enables extra features that would not be available under the current solution—being isolated means breaking free from the current regulation (and monopoly). To further enhance the need for isolation, the ADCx model recommends the deployment of Direct Current (D.C.), covered in principle 4, making the need for separation of the A.C. grid even more appealing.

PRINCIPLE 3: AUTONOMY - WHENEVER POSSIBLE

Every entity under the ADCx model, picogrid, nanogrid, and microgrid, should aim for a degree of autonomy - their ability to function and provide for themselves for an established set of essential services during an established period (e.g., one day, one week, one month). Being autonomous does not imply isolation from other network peers; it simply implies being capable of functioning for the essential requirements.

There are several benefits of interconnecting with neighbours through a nanogrid or microgrid. It helps improve network resilience, enables power trading or bartering, strengthens community collaboration, facilitates information exchange, improves habits, and many more. When a householder cannot achieve autonomy, they can still count on their neighbours or local service providers (nanogrids and microgrids). The ADCx model encourages the deployment of local power cooperatives to store or supply power when needed. It supports local economic development and *circular economy* as described in *principle 7.*

PRINCIPLE 4: RUN EXCLUSIVELY ON DIRECT CURRENT, 'D.C.'

When the goal is to achieve sustainability, the direction of the flow of the electrical charge becomes unimportant; however, several other critical aspects must be considered. The main reasons for selecting the D.C. system (instead of A.C.) are:

a) Supports the isolation and the separation of concerns (*principle 2*). Since DC has different electrical characteristics, it cannot co-exist with the status quo. Therefore, it helps to minimise compliance issues and liabilities that are major roadblocks. Once isolated, there is no need to duplicate cables, deploy inverters, controllers, and several other technical and legal concerns;

b) D.C. eases the transition to cleaner sources. There are losses between 5% to 20% when A.C. power is converted to D.C. power. The strong reliance on electronics by renewable sources to control and overcome inherent stochastic problems creates a synergy with D.C. power. Eliminating unnecessary conversion losses is extremely important to lower costs and become competitive.

c) D.C. power does not have a frequency problem when combining mixed sources. Given the existing challenges, it is unlike a single power source that will fit all the user needs during all times of the day and seasons. D.C. is compatible with both renewable and non-renewable power sources. Most renewable sources generate power intermittently (solar and wind), and others do not (geothermal, hydro, biodiesel).

d) D.C. power can be stored directly in D.C. batteries without conversion. Conversely, there is no equivalent storage system for the A.C. grid, implying it needs to undergo two conversion stages, A.C. to D.C. when storing power; and D.C. back to A.C. when an appliance requires stored power. It indicates that the D.C. system's power supply and storage integration are enhanced, creating efficiency opportunities and reducing operational losses.

e) In the heat of the "*war of the currents*" in the 1880s, only a few types of appliances existed. No transistors, no power electronics, no air conditioners. Power conversion could only be achieved via transformers, which became the determinant factor that led to the existing A.C. grid [633]. Today there is a very different scenario, where appliances have multiplied manifold. Most of them, e.g., refrigerators, air conditioners, vacuum cleaners, and hundreds of others, use D.C. motors. They have higher efficiency and power-to-size characteristics. DC-based lighting (LED) is as much as 75% more efficient than incandescent lighting. D.C. electricity enhances power efficiency in most of the existing applications.

f) The transition to the D.C. system will create more space for competition and motivation for lowering emissions. The status quo is heavily controlled by the state due to monopoly. Electricity is supposed to be a means to improve living conditions – not a means to destroy nature to satisfy some stakeholders. Small and decentralised D.C. power plants overcome the monopoly problem.

g) Adopting the ADCx model will drive manufacturers to produce more D.C. devices (or hybrid) to become competitive. Power hybridity is an important aspect during the transition phase. The main reason D.C. appliances are not found at a large scale today is a result of the biased regulations. ADCx creates a new market for D.C. appliances, which will consider embedded and disposal emissions, apart from operational emissions.

h) Several large-scale field applications today already make use of D.C. electricity. Power transmission lines over long distances have been using D.C. for decades – this was not the case a century ago when power electronics were unavailable. If the 'war of the currents' took place today, a different outcome would be highly possible [633]. There are no longer technical barriers. D.C. power systems have been making significant advances in data centres, railways, automotive, and community applications. D.C. power is already in use at the "bottom of the pyramid" in many places in Asia and Africa where there is no access to the grid [634, 635, 636].

i) The transition to electric vehicles indicates the advantages of D.C. power since renewable sources can charge the batteries during the day, and the car becomes a microgenerator at night. It is a faster and more reliable microgeneration source towards best practices of *circular economy*. In Europe, smart villages that use D.C. power are being designed, and electric vehicles are envisaged as part of the storage system for renewable power [637].

PRINCIPLE 5: CLEAN METHODS OVER CLEAN SOURCES

The BAIoTAG framework focuses on echo-sustainability, not on the notion of renewables replacing fossil fuels. The net-zero balance is an optimal condition that cannot reach the industrial scale on day 1. Sustainability reaches far beyond carbon dioxide emissions during the operations phase; thus, there is no such a condition as "fully clean power grid" at an industrial scale. Every power generation system has embedded, embodied, and disposal emissions, apart from operational emissions.

Being renewable is neither a guarantee of being sustainable, carbon-neutral, nor reliable [638]. Sustainability refers to deploying methods that prioritise environmental and community needs in the short and long term. As it stands, there is no reliable tool capable of determining sustainability for any given application, from mining the raw material to manufacturing, operations, and disposal. The life cycle includes extraction, manufacturing, transportation, assembling, installation, operations, decommissioning, and disposal. Every single phase has emissions associated with it.

For instance, wind farms are often regarded as a renewable system; however, the wind itself is the only renewable item among hundreds of components in a wind farm. The concrete, earthmoving, steel, blades, engine, and many other components are not renewable, and they are all high energy-intensive and have an immediate effect on the environment. The same rationale can be applied to solar, thermal, hydro, and nuclear plants [28, 495, 639]. Each component had to undergo a long manufacturing process before installation. In most cases, it involves parts from different countries, and quality data are not available, emissions forensics are not possible.

PRINCIPLE 6: SECURE COMMUNICATION CHANNEL

Small-scale power distribution systems require strong user collaboration and sharing of sensitive information between multiple systems. It implies the need for a reliable platform to secure data in transit and at rest. Secure communication is key in any data system; however, it becomes even more critical when consumer data between untrusted parties (network peers) without a centralised third party. Millions of cyber data breaches happen annually in every industry – and only a fraction makes the news [640, 641].

Blockchain technology aggregates several features under a single construct, including digital signature, non-repudiation, authentication, anonymity, data provenance, anti-tampering, and timestamping. Several Blockchain applications have been proposed in the energy sector and potentially transform the segment [200, 201]. Typical applications include peer-to-peer energy trading, network management, certification of GHG footprint, information security system, energy crypto tokens, and business models for capital raising. Blockchain-IoT energy trading platforms have already been proposed and implemented [213, 214, 211, 212].

The exchange of classified information among untrusted peers is highly challenging in a decentralised power system. The need for stratified consumption, load balancing, power supply, and storage is paramount to optimising resources and enabling peer-to-peer energy trading. Improving consumption habits, energy efficiency, rationalisation, task automation, and sending user educational feedback is key to promoting a reduction in consumption.

Blockchain technology can provide a secure communication channel within the neighbourhood. Prosumers' machines can exchange sensitive data without risking data confidentiality or integrity. As data is always encrypted, structure and semantics are known only to peer machines to maintain interoperability. Individuals can access local information, and only authorised machines with specific tokens can access the Blockchain. A.I. and IoT agents communicate via MQTT protocol (Message Queueing Telemetry Transport). Data transformations, encryption, and publishing of the results in the Blockchain automatically occur at established intervals (e.g., 1 minute, 10 minutes).

Some peers can verify accuracy and authenticate the user, while others can validate the transaction while running specific applications to aggregate and publish the results. On the other end, machines can extract information and communicate with other subsystems. Blockchain ensures data integrity, provenance and privacy at all times and without a third party.

PRINCIPLE 7: PROMOTE LOCAL ECONOMIC DEVELOPMENT (LED) AND *CIRCULAR ECONOMY*

Circular economy and Local Economic Development (LED) are foundational assets in developing an autonomous and small-scale power system for a community. Whereas electricity is essential for regional development, cleaner methods are compulsory for sustainable development.

On the other hand, strong evidence proves the correlation between GDP and emissions per capita [642, 643, 644]. Economic development and environmental depletion have been closely connected over the last century. Nations with higher IDH and GDP per capita are the same ones with the highest emissions per capita, with a few exceptions (e.g., Middle East countries). Most advanced economies became "developed" as a result of poor practices against the environment. Changing this paradigm is a foundational requirement for reaching sustainability.

Traditional business models have always prioritised higher performance and the economy of scale as pre-conditions to lower costs and stimulate consumption. However, emissions have been released in the same proportion of goods and services produced, commercialised, and disposed.

The self-destructive economic model, inadequate education, and ineffective laws to provide long-term protection have become the major root cause of GHG emissions. Reversing this trend requires a paradigm shift in consumption habits and lifestyles. Rising user awareness through environmental education is key to reaching sustainability. Governments and large corporations have many intertwined interests that conflict with effective policies for lowering emissions. A bottom-up approach, spearheaded by individuals and the community, can be a game change towards sustainability.

Local Economic Development (LED) focuses on mobilising stakeholders to become partners in a joint effort to improve the local economy and thus increase competitiveness [645]. It may include public, private sectors and civil society within the local community. It has a strong bottom-up orientation, driven by local stakeholders. LED is about exploiting local resources to improve local competitiveness. It enhances the attractiveness of products and services produced and consumed locally.

On this same track, *circular economy* moves away from the traditional mindset of 'take-make-use-dispose-pollute' towards recycling, remanufacturing, reusing, and creating local opportunities which did not exist before. It is a small-scale and local approach. *Circular Economy* demands sustainable growth, justifiable lifestyles, and a much longer-term view of benefits and liabilities.

Circular economy promotes the reuse of resources. Energy-from-Waste (EfW) or Waste-to-Energy (WtE) are initiatives toward generating power and heat by treating and processing the waste into a fuel source [589, 590, 591]. It is a form of recovery of energy fully aligned with *circular economy*. Fuel from plastic, gasification, pyrolysis and thermal depolymerisation are some of evolving technologies that can generate fuel and power from waste without releasing emissions (combustion). It can provide reliable, decentralised, low-carbon electricity to power local communities [591]. Transforming waste into energy is key in supporting c*ircular economy,* allowing the value of goods, resources, and materials, to be useful longer, while avoiding unnecessary fossil burning, and reducing waste and resource use [646].

Small-scale electricity power plants locally managed can become a magnet for attracting local and sustainable business opportunities. Since it allows energy trading and bartering, it can trigger many other opportunities within the community. It will encourage wider adoption of *circular economy* concept. The need for skilled labour, the continued quest for finding more eco-friendly energy sources, new mechanisms for lowering consumption, and clean innovation, are some of the new business niches that can benefit from a *circular economy*. LED and circular economy can help improve collaboration, re-educate users towards creating a sustainable business, provide tools for measuring and monitoring emissions, and continually improve habits.

PRINCIPLE 8: ENABLE PEER-TO-PEER (P2P) TRADING

P2P energy trading (and bartering) refer to exporting or importing electricity from a neighbour. It requires a secure platform for measuring, managing, controlling, and ensuring data provenance. P2P energy trading presents extensive technical and legal complexities compared to the A.C. public grid. Under the current system (A.C.), electricity is produced by a group of interconnected power stations, transported through long transmission lines (high voltage), converted, transformed, and integrated into the distribution grid (low voltage). Although the producing facilities may be privately managed, the entire ecosystem is strongly subject to governmental control. In the electricity business, the boundary lines between public authority and private capital are blurry and twisted, creating an accountability problem. In a way, the government, financers, and infrastructure service providers have found ways to outsource and conceal the "combustion" activities.

For feasibility reasons, the power systems design model is centralised and heavily based on fossil fuel combustion, without sufficient emission mitigation measurements. That enables affordable electricity prices and high availability. Paying the bills becomes the only accountability for the user. However, on the downside, it backfires by releasing large amounts of gases into the atmosphere, which has become the principal cause of global warming [626, 405]. Climate change and environmental depletion are consequences. Under the current A.C. grid, the concepts of energy trading or bartering are not even applicable since they would conflict with the services provided by the utility provider.

In developed economies, the excess electricity generated by a prosumer (e.g., from solar photovoltaic) can be exported to the grid at a standard feed-in tariff rate. Although there is some financial incentive, the Energy exported is unlikely to help reduce emissions from an environmental standpoint. The crest of the peak hours happens after the sunset. It becomes unfeasible for large power stations to increase or decrease capacity at different times of the day. They do not have the flexibility to change power outputs at their wish. This is referred to as the duck curve problem [35].

A new system must introduce advanced features to become attractive and competitive with the status quo. That is where energy trading or bartering becomes extremely important. Deploying incentive mechanisms through game theory concepts embedded in the consensus protocol is an option [34]. A game theory solution has been proposed by [647], capable of solving the multi-agent agent trading problem. Mixing energy sources, predictive modelling, and storage solutions can counterbalance the potential duck-curve problem associated with P2P energy trading and reaching net-zero emissions. It fully supports the concept of *circular economy.*

P2P energy trading can be achieved by coupling IoT and Blockchain technologies. A hybrid Blockchain can provide control access among several agents for communication while enabling a payment rail for energy trading. Another approach is P2P energy bartering for enhancing network resilience instead of focusing on financial incentives. It is simpler since it does not require all the financial instruments, but it still requires extensive energy management among prosumers sharing the same microgrid [648].

PRINCIPLE 9: STIMULATE LOW-CARBON LIFESTYLE

Incentives and educational feedbacks are essential tools to guide people through a low-carbon lifestyle with less GHG emissions and pervasive technologies. Although technologies bring several short-term benefits in the present, the liabilities are abstract, relayed to the distant future, and affect the entire planet. Thus, solving the emissions problem requires changes in liaising with technology, and raising users' awareness is the first step towards a low-carbon culture.

Given that GHG emissions are released in the same proportion as goods and services are produced, reducing global emissions implies in lowering consumption rates – or rationalising it. Conversely, the largest corporations worldwide in oil & gas, tech giants, consumer goods, and financial work as a team in full steam to stimulate emissions. Thus, it would be unreasonable to expect governments to implement any form of rationalisation against their most revered partners. So, it is now up to the individuals and communities to find ways to protect the environment.

A bottom-up approach can be used to raise users' awareness through educational feedback. The individual shall learn to distinguish between (i) essential and non-essential acquisitions, (ii) technologies that promote well-being versus those that promote profits, increase in consumption and emissions, and (iii) educated consumption versus mindless consumerism. Customised feedback can educate individuals through the learning curve, so they can find if the pros in the present outweigh the cons in the long term, shielding the user against media manipulation, propaganda, and fake news. Educational feedback should neutralise the stimulation from an entire ecosystem around production and consumption.

The current scenario in the electricity industry is a classic non-cooperative game, where all players have very little to gain from saving electricity, which can be translated to no motivation for reducing consumption or emissions. Investments in clean Energy are ruled by short-term economic strategies and a policy system that promotes emission freeloaders. On the other hand, small-scale decentralised D.C. power plants built around electricity cooperatives could bring more realistic results and lead to significant emissions cuts [649].

If game theory strategies are used in a power plant cooperative environment (e.g., microgrid), then several incentives can be embedded in the consensus protocol to promote lower consumption.

Game theory is a mathematical approach to studying social interactions among individuals or groups. The strategies chosen by each player lead to payoffs, which may represent gains, losses, or compromises. People are willing to reduce emissions as long as they understand the consequences of their choices and potential risks from climate change – but also that the mitigation strategies will not cost them their jobs. Once they perceive the risks from climate change, and there has been plenty of evidence [19, 20], floods, heatwaves, glaciers and ice polar melting – all these can influence people towards better habits. As put by [650]: *cognitive clarifications in the support for reducing greenhouse gas emissions are more powerful than economic or partisan heuristic ones"*.

The global emissions problem is strongly correlated to strategies deployed by governments and the corporative world. Stakeholders have nothing to gain in the short term by changing strategies and cutting emissions, leading to the perpetuation of the problem.

Air conditioners provide instant comfort to the user - however, in the background, it is responsible for a list of GHG gases that can last hundreds of years in the atmosphere. The vendors, government, utility companies, or consumer protection associations will not inform the user about the long-term effects on nature. As the consumer goods producers, they have nothing to gain in raising users' awareness – since they are all co-beneficiaries of the ecosystem. Although indirectly, they all profit from emissions.

Instead, a label tag informs the consumption rates during its operations lifecycle [651, 652]. However, household consumption of domestic appliances is a small fraction of a much bigger problem. Whereas the householders' electricity consumption represents around 5%, the industrial sector represents 76.5% of the global emissions [351, 352]. So, the label system brings several outcomes: it stimulates more sales by inducing the consumer to think that swapping appliances would help the planet to become greener; it masks all the emissions released by each of the suppliers during the pre-manufacturing and industrial stages (e.g., raw material mining, rubber and plastic transformation processes, transportation); also, it covers up for the emissions after the product disposal. In short, the label system slightly tackles 5% of the problem while providing a cover-up for the greater portion (76.5%). It helps the vendor greenwash their products while worsening the global emissions paradigm.

Developed nations produce electricity mostly through the combustion of fossil fuels; through subsidies, electricity is made inexpensive and widely available to the public as part of regional political planning. Since it powers every other industrial sector, the electricity segment has become the major source of global emissions, which is nothing but a natural course of events. Nevertheless, the correlations between power generation, production of goods and services, and GHG emissions are not made clear to the public. Pervasive technologies transform the individual into a permanent consumer target, attracting people to media, apps, games, and any form of digital entertainment. There is always some marketing campaign running in the background, motivating people to acquire and consume more goods. Low energy prices coupled with pervasive technologies are key drivers for consumerism and, thus, leading to more emissions.

The largest corporations (e.g., Apple, Amazon, Microsoft, Google, Facebook) specialise in stimulating consumption. Some create the media devices, while others create the apps, digital advertising, and eCommerce platforms. Their products trigger the users to engage in activities that lead to indiscriminate consumption – from which they derive their profits. They are all freeloaders on the global emissions problem – since they do not produce the emissions; however, they stimulate more productivity and consumption, which translates to emissions. Most landfills would be empty if not for the software, media, online retailers, and digital advertising industries did not exist.

Determining consumer behaviour towards electricity consumption can be challenging since it has many underlying values. The criteria for grading the benefits versus liabilities may be influenced by beliefs, dogmas, myths, principles, socio-cultural aspects, or baseless assumptions. Intangible values and influences may not be identifiable or disentangled. Verbalisation, articulation skills, and typification can become barriers [653]. Personal preferences, time-saving factors, comfort, pleasure, convenience, routine, and meaning can significantly vary over time, location, and environmental education. As the level of abstraction is high, the first step is to quantify, followed by feedback and education.

Real-time feedback is essential for user education during the learning curve. It can trigger better actions, improve behaviour, prevent problems, give insights, and present new perspectives to the user. Feedback is highly useful when users continually make baseless assumptions, leading to undesirable consumption behaviour. For instance, should a consumer store food in the fridge for a few days or 1-month? What are the benefits and cons? What are the underlying assumptions? Fear of food shortage? Or time-savings? Would it be worth spending extra Energy to satisfy such assumptions? Patterns can be carried for a lifelong. There are many areas where technology can help consumers to improve their behaviours.

PRINCIPLE 10: CLEAR METRICS, REPORTING & VERIFICATION SCHEMES

Every manufactured object has embedded emissions associated with the raw materials and industrialisation processes. Buildings have embodied emissions on every material and service before and during construction. Objects and buildings also have emissions associated with disposals. The term *carbon footprint* shares similarities with *GHG footprint*; however, contexts may differ.

Reducing emissions at a household level, facility, corporation, neighbourhood, city, state, national and globally are distinct problem classes. They have different variables, constraints, sources, sinks, actors, and uncertainty ranges. They all have relevance to accessing climate mitigation actions; Packing all these classes of problems under a single category creates potential misunderstandings and does not contribute to the solutions. As long as the climate policies remain centralised and mismanaged, with no clear accountability boundaries for each actor, and without reliable mechanisms to manage the global commons, GHG emissions levels are fated to worsen.

GHG footprint refers to the total GHG emissions related to a product, facility, person, service, or activity. It can be calculated to a specific event, such as a trip, process, or method, during a period. For instance, a GHG footprint calculation for a facility (house, factory, building) must account for all emissions embodied in the building (a) before the construction, embedded in each material and associated transformation process, (b) during the construction, (c) renovations, replacements and building maintenance, (d) consumer goods, appliances, and any manufactured product inside the house, (e) operational emissions for the household during the lifespan, such as electricity or fuel, and then (f) emissions related to disposal and waste.

The GHG footprint calculation for a householder requires several inputs, such as building sizes, materials, occupancy, living styles, income, age, appliances, times, seasons, and many others. The embodied emissions for the building envelopment can represent 65% of the GHG footprint for a Zero-Energy-Building (ZEB) [654]. All these variables affect the carbon footprints. The quantification of socio-economic household characteristics is often associated with the per-capita carbon footprint. The decomposition of the carbon footprint into the distinct consumption domains reveals that income distribution is linked with carbon footprint [79].

Calculating the carbon footprint for an enterprise requires a detailed GHG inventory, including local, remote, outsourced, or indirect emissions. A partial carbon footprint calculation must be properly indicated to avoid misunderstandings. Emissions can be released by stationary, and mobile sources, from electrical use, non-electric use (e.g., fossil fuel, biomass), or fugitive emissions. Emissions can be measured directly or through calculation. It can be a simplified calculation based on assumptions embedded in a simulation tool to establish a baseline, a starting point, so a trendline can be built from tracking it over time. Alternatively, it can be an advanced calculation.

The GHGP (greenhouse gas protocol) standard became a reference for calculating organisational carbon footprints [373], providing an accounting system, reporting framework, sector guidance, calculation tools, and training for businesses and the government. Several organisations, such as EPA (Environmental Protection Agency, USA), The Nature Conservancy [374], and British Petroleum [375], created their version of carbon footprint calculators on the Internet for individuals. Such calculators allow users to compare their estimated carbon footprints with the national and world averages. The Climate Registry provides a consistent framework for companies and organisations across North America to measure and publicly report their Greenhouse Gas emissions [655].

Since the bulk of GHG emissions is released away from densely populated areas, users are unaware of the correlation between their acquisition of goods, consumption, and disposals. GHG footprint calculators accounting only for a portion of the life cycle can be misleading if not properly indicated. On the other hand, a comprehensive GHG calculation may become very complex. Knowledge-intensive calculators can reveal the lifestyle and activities of the householders. However, engaging people to use this type of calculator, especially more than once, can be challenging [656].

The standardised GHG equivalencies for daily activities [376, 377] allow organisations to create carbon footprint calculators [378]. Some online versions of these calculators are sophisticated and serve as anchors to promote and attract business [379, 380, 381]. It supposes to trigger users to improve behaviours. REAP Petite uses a bottom-up approach, by first calculating the individual impact to better estimate the entire household footprint

[382]. GHGCal can calculate Methane (CH_4), Carbon Dioxide (CO_2), and Nitrous Oxide (N_2O) gas released from industrial activities of many types of organisations [383].

It is debatable which gases should be included in the GHG footprint calculation. Data availability, quality, and complexity become roadblocks if all the gases are included. Some authors suggest that only carbon dioxide (CO2) and Methane (CH4) are included [657]. There is a trade-off to be considered on a case-by-case basis. The infrastructure sector is still in a learning process [658] and still evolving.

Reaching sustainability requires the users to take accountabilities for all the emissions associated with their acquisitions and consumption. A GHG emission calculator can trigger better-informed decisions and the adaptation of consumers' lifestyles. It helps to create a baseline, a starting point, so users can act and improve upon it.

PRINCIPLE 11: RELIABLE MITIGATION SCHEMES

GHG emission mitigation refers to any action or mechanism intended to (a) reduce, (b) remove, or (c) compensate for undesired emissions. It can involve direct or indirect emissions from an individual or organisation at any level, household, facility, neighbourhood, city, state, national or global. Mitigation actions must be tackled closest to the sources as possible to avoid inefficient schemes from the past [400].

Lowering global emissions requires action at all levels. Individuals can raise awareness to reduce non-essential acquisitions with proper tools and infrastructure. Communities can pressure manufacturers to improve processes and avoid or mitigate their emissions. Communities and manufacturers should push for law changes. Decentralisation of climate policy, distributed power systems, tools and infrastructure to support the user to a lower carbon culture must be in place. Each sub-state jurisdiction (districts, city, region) should take accountability for the emissions in their territory. Conversely, the worst-case scenario is the continuation of the existing ecosystem, where decisions at a national level keep promoting indiscriminate production, free-riding, more consumption, and consequently, more emissions.

Carbon offsetting (or carbon marketing) was introduced by the Kyoto Protocol in 1998 (Article 17) and later modified by the Paris Agreement (Article 6). It approved carbon offsets as an approach for governments and private companies to obtain carbon credits that can be negotiated in a marketplace and through voluntary cooperation [397, 629]. Carbon credits have been criticised for inefficiency and used for greenwashing purposes [659, 660]. Negative emissions provide a revenue stream for some stakeholders while enabling others to emit more emissions. Negative emissions sound like a "*burn now pay later*" market campaign version to extend the global environment problem as much as possible [401, 398].

According to Oko-Institute, a German research group that analysed carbon offset: "*our results suggest that 85 percent of the projects covered in this analysis and 73 percent of the potential 2013-2020 Certified Emissions Reduction (CER) supply have a low likelihood that emission reductions are additional and are not over-estimated*" [400]. Several carbon standards and certification agents have emerged in the past decade [661, 662, 663]. In 2015, the UNFCCC (United Nations Framework Convention on Climate Change) launched a dedicated website (https://offset.climateneutralnow.org/) where organisations can calculate their carbon footprint, select a project (e.g., wind, solar), add a certificate of emission reduction (CER), pay, and receive the attestation for carbon neutrality [664].

The Oxford Principles for Net Zero Aligned Carbon Offsetting [665], launched in 2020 by the University of Oxford. The Science Based Targets (SBTi) [666], a collaboration of WRI, CDP, WWF, and U.N. Global Compact. Both initiatives argue the relevance of moving beyond offsets towards offsets grounded on carbon sequestered from the air, such as CO2 Removal Certificates (CORC) [667].

The 'Puro Standard' for carbon removal uses science-based certificates, which are supposed to represent actual carbon that has been removed from the atmosphere. A service supplier conducts the verification process according to the set of rules established in the standard. It includes scientific methods, measurement tools, carbon budgeting, and quantifying the removed carbon for the product or process, taking a cradle-to-grave lifecycle approach [668, 669].

The Gold Standard for Global Goals, or GS4GG, is a trademark from the Gold Standard Foundation that creates standards around sustainability. They are headquartered in Geneva and provide compliance certification to organisations in specific areas. The design and planning should meet the GS4GG principles and requirements followed by a standard certification procedure, including validation and verification bodies [670, 671].

Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide. Biogenic-based sequestration (afforestation and reforestation) techniques can be considered mature [546]. Bioenergy Carbon Capture and Storage (BECCS) is another promising *negative emission* approach discussed widely in the literature [672, 548].

Every power generation system carries embodied emissions from its building parts, materials, construction, decommissioning and disposal. Renewable source solutions do have upfront environmental costs. For instance, a solar park or a wind farm system can take around 1-year to 5-year greenhouse payback time (GPBT) [673, 493, 674, 639]. However, there are other environmental consequences beyond emissions to be considered.

PRINCIPLE 12: PROMOTE CERTIFICATION & REWARDS

The BAIoTAG framework builds up from an individual level, the householders through the national and global levels. There must exist enough motivation for the user to adopt a pro-environmental lifestyle. Rewards can address the individual, household, or neighbourhood; they can be financial, discounts, or recognition from the community. Certificates can account for users progressing in the sustainability scale or reaching net-zero.

Design decisions such as building shape, materials, sizes, and every aspect counts in calculating the GHG footprint. All these characteristics impact user behaviour and daily consumption patterns. Prioritising aesthetics over energy efficiency remains a prevalent practice. Steel and cement account for approximately 14% of global GHG emissions [675, 676, 420, 419].

Sustainability remains an abstract concept around prioritising the environment and meeting the present human needs without compromising future generations and the planet [307]. It is often associated with products, services, processes, manufacturing facilities, or organisations achieving sustainable goals. A closely related overlapping concept is the sustainable development goals (SDG), introduced in 1992 during the U.N. summit in Rio de Janeiro. The SDGs are a call to action for the world, with 17 goals, encouraging stakeholders to take more sustainable approaches to the planet.

Performance indicators can be implemented on many fronts to create more tangibility. Individuals (and organisations) would gain awareness of the progress of their achievements, and a baseline profile can be established. Although there is neither shortage of standards nor certification options, the current figures for global GHG emissions show that sustainability remains a remote concept. Many organisations explore sustainability merely for business opportunities.

Popular sustainability standards include the ISO and GRI [677]. ISO standards cover social, economic, and environmental concerns focusing on sustainable practices [678]. For instance, ISO 14001 standards, listed under Environmental Management System (EMS), cover climate action (SDG 13), ISO 15001 standards refer to affordable and clean energy (SDG 07), ISO 24000 addresses sustainable procurement and consumption (SGD 12), and others. GRI is the second-largest institution, a de facto global sustainability reporting organisation. GRI standards focus on economic, social, and environmental sustainability and include guidelines [679, 680]. Among several others, GRI standard 302 addresses climate vulnerability and Action (SDG 13);

The most popular certification bodies on sustainability are: Lloyds Register (LR), Société Générale de Surveillance (SGS), Bureau Veritas (BV), Det Norske Veritas Germanischer Lloyd (DNVGL), , British Standards Institution (BSI), and the Technischer Überwachungs-Verein (TUV) [677]. They all provide supporting services to companies to register and obtain certified compliance with GRI, ISO, or other sustainability standards.

Householders and organisations must be motivated toward reaching sustainable goals. An online survey in 2015 of 30,000 consumers covering 60 countries found that "*two in three consumers are willing to pay more for products or services from companies committed to making a positive social and environmental impact*" [681]. However, without a comprehensive infrastructure and supporting tools, users have no mechanism to decide on what products and companies are sustainable.

The energy efficiency labelling system [651, 652] for household appliances promotes sustainability, although it has several drawbacks. It slightly helps reduce daily household emissions, which represent about 5% of the global emissions, while providing cover for the greater portion of the problem (76.5%). It stimulates sales and helps vendors greenwash their products while worsening the global emissions paradigm [351, 352]. The greater portion of the emissions is linked to the industries that transform the materials and produce the goods, not the householder. The planet does not benefit from a user swapping for a more economical appliance. On the contrary, a new appliance carries huge amounts of embedded emissions that are not displayed on the energy label. It may take ten years to compensate for the embedded emissions from the vendors, retailers, transportation, and disposal; by then, the householder would likely need a new appliance.

Certificates can prove the eco-sustainability status of each entity for the entire historical period. Since it uses a Blockchain, data provenance, auditing, and integrity are guaranteed without human intervention. Depending on the consensus rules agreed upon, only the nanogrids and microgrids service providers may be able to generate and send the certificates to the user. The key benefits of eco-sustainability certificates are: (a) to motivate users to improve consumption habits, (b) to create more value for their properties according to their efficiency on energy savings, and (c) The higher the efficiency, the higher the prestige and recognition from the community, (d) the lower the consumption, the better to the environment, (e) enables communities to compete, on a healthy manner, on who gets the best energy efficiency for a given period, or a certain geographical region.

5.3.4 BAIoTAG Framework – Overview

The BAIoTAG framework builds upon the ADCx model and BAIoT system, complementing each other, as shown in Figure 88. The major goal is to enable users to achieve sustainability within their premises or neighbourhoods. The ADCx model deploys small-scale D.C. autonomous power grids with isolation from the A.C. grid. While the BAIoT model provides the intelligence, analytics, trusting communication and payment rail for peer-to-peer energy trading. Together, they form the BAIoTAG framework, adding other benefits such as *circular economy*, consumption rationalisation, user education, eco-sustainability certificates and more.

Under the BAIoTAG framework, each power consumption, generation, or storage event should be registered in a local database and transferred into a Blockchain ledger. The GeSLOC engine will measure and monitor performance continually. The data is grouped, timestamped, encrypted, and hashed before being published in the ledger. Only machines with access rights can process and act on the data but never modify it. On a chosen data window (e.g., weekly, monthly), all the data is aggregated for each entity, picogrids, nanogrids, and microgrid. A file with the power history for each entity is automatically generated. Performance and efficiency are calculated based on the number of people, size of the entity (e.g., house), and consumption for each use category.

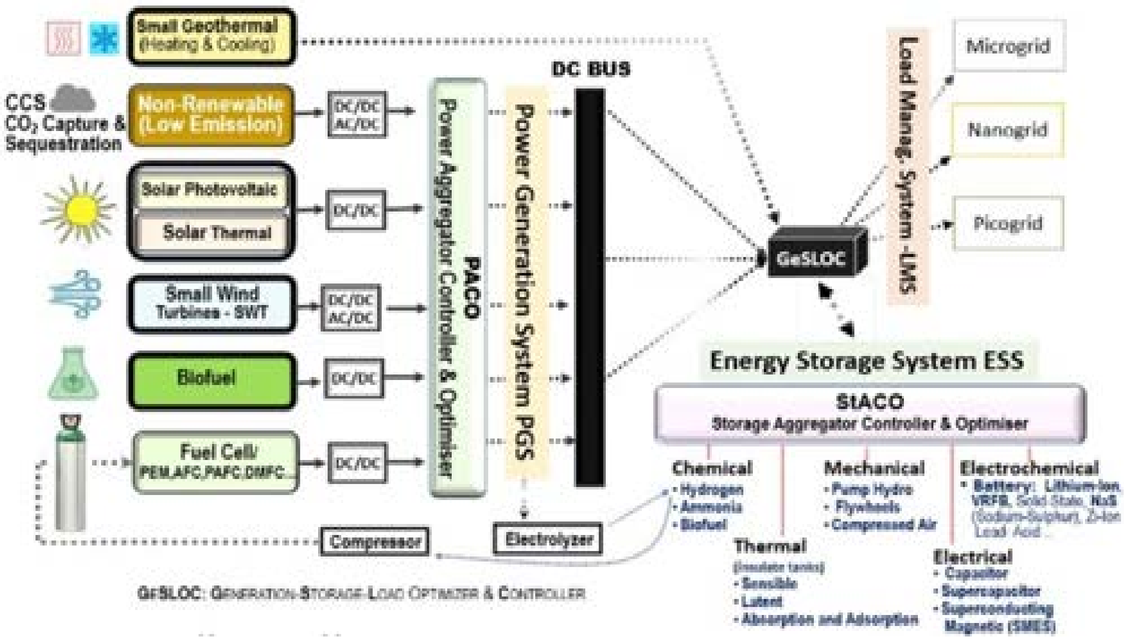
Several indicators are created for the householder (or a community of users). Upon request, the system can generate certificates proving the facility's eco-sustainability status over a period (e.g., a 1-month). The issuance of the eco-sustainable certificates relies on the consensus protocol for the whole community of users.

An autonomous D.C. microgrid (ADCm) can serve 250 nanogrids, covering around 62,500 dwellings. The precise number of affiliated entities and coverage area may vary according to geographical conditions, available technology, and feasibility studies. An autonomous D.C. nanogrid (ADCN) can serve 260 dwellings and is restricted to a street block or a multi-unit building since the goal is to be autonomous and sustainable. Microgrids and nanogrids can cover residential, commercial, and small industrial facilities. A picogrid (ADCp) is a single dwelling and contains several femtogrids. Each femtogrid represents a usage categorisation. ADCx recommends nine use categories, one for each femtogrid: (a) lighting, (b) food preservation, (c) cooking and water heating, (d) labour-saving and mechanical tools, (e) education, communication, gaming, (f) space cooling and heating, (g) hygiene, (h) outdoor entertainment and (j) electric vehicles.

Each entity (picogrid, nanogrid and microgrid) has a Generation-Storage-Load control (GeSLOC) system, which communicates with all the subsystems and provides control and optimisation functionalities across all the ADCx subunits (power generation, storage, and load management).

Beyond the power control and optimisation capabilities, the GeSLOC also houses all communication mechanisms among the many subsystems. Blockchain-AI-IoT enables peer-to-

Figure 88: ADCx-BAIoT System Overview



peer energy sharing, user feedback, and communication with other network peers. By leveraging all these concepts and technologies under a single framework, BAIoTAG enables consumers (and prosumers) to achieve sustainability within their local areas.

5.3.5 MAJOR CONTRIBUTIONS OF THIS STUDY

This section presents the most relevant and unique contributions from the BAIOTAG framework:

- It provides a new pathway for people willing to act to reduce their emissions and make their contribution to tackling the emissions problem without relying on governmental actions.
- It triggers decision-makers to create more efficient laws for protecting the environment.
- Enable communities to become self-organised and solve their energy requirements locally.
- Contributes to *circular economy*, such as reusing solar panels, wastewater for biofuel, biomass, and recycling.
- Create stronger collaboration within a neighbourhood, facilitating the exchange of experiences, discoveries, and learned lessons and encouraging new approaches.
- Encourages more local businesses, electrical cooperatives, local and small-scale service providers, and local jobs for microgrid and nanogrid network operators.
- Enable householders to measure their carbon footprint, take corrective actions, and get their properties certified as eco-sustainable (e.g., net-zero emission for 12 months).
- Improve consumer habits - by discouraging time-wasting activities (e.g., excessive social media) and encouraging healthier activities.
- Reduce energy waste and save electricity by avoiding appliances that bring no added value to the user.
- Motivates healthier competition among neighbourhoods to improve their sustainability.
- Enables resource sharing, which helps to improve system reliability and availability.
- Forces vendors to produce D.C. appliances, avoiding unnecessary conversions and power waste.
- Enables peer-to-peer data sharing between machines without losing privacy (the opposite of data aggregators).

- BAIoTAG is replicable, capable of crossing borders and being deployed anywhere.

5.3.6 CONCLUSION

Global emission is a global problem with multiple root causes; although the energy sector is the main source, it is not a root cause. The driving forces that lead the energy sector to release 82% of the global emissions are linked to low consumer awareness resulting from a flawed educational system coupled with a socio-political ecosystem that prioritises short-term economic development at the expense of the environment. With over 75 million organisations stimulating emissions, such as retailers, advertisers, media, and consumers surrounded by pervasive technologies, it is highly expected that emissions will keep rising even faster. The existing mitigation actions promoted by the U.N. affiliates, such as the transition to renewables and carbon market, have been proven ineffective and inefficient, enabling the problem to worsen.

Reversing this trend requires a bold plan to move away from the current model. It requires a new infrastructure for the electricity supply followed by tools and mechanisms to support users to move towards a low-carbon culture, lower consumption, and cleaner methods. The BAIoTAG framework addresses the seven root causes of emissions and presents the 12 principles on which the new power system must be built. It enables users to educate themselves and break free from the status quo. It provides the tools, the infrastructure, and the conditions to users reach sustainability without awaiting governmental action. It also minimises confrontations with the existing codes and creates extra space for local economic development, the ideal conditions to boost the *circular economy*. In a bottom-up approach, BAIoTAG introduces educational feedback, analytics, sustainability certificates, rewarding schemes, and healthy competition. Users can measure and control their GHG emission footprint, raise awareness, and re-evaluate their consumption habits. The framework creates a pathway for individuals and communities to take action and achieve sustainability independently, without relying on governments or new laws.

Chapter 6: A Comparative Case Study for the deployment of Machine Learning in Picogrids, Nanogrids & Microgrids: BAIoT over ADCx

Abstract — In a small-scale, decentralised, and autonomous power system, it becomes critical to anticipate outcomes, assess the options, and act preventively. Power and load forecasting are paramount in overcoming the stochastic nature of variable renewable energy (VRE) sources and user uncertainties. There are neither path nor equipment redundancies, and the power backup is limited. The system must use the local resources in the best way possible to overcome power shortages and faults and meet users' needs to the best of its abilities. Power and load forecasting can greatly enhance performance in small-scale autonomous power systems isolated from the public grid. This case study aims to provide concrete, contextual, in-depth insights about deploying machine learning technologies for predictive tasks in autonomous *microgrids*, *nanogrids* and *microgrids*. Six case studies have been conducted, and results and comparisons are included. This comparative case study follows other studies by the same authors, the ADCx model, the BAIoT system, and the BAIoTAG framework. The importance of this study is in demonstrating the usefulness of using machine learning to solve real-world problems by using real-life data. To the authors' best knowledge, this case study is unique in deploying machine learning technologies in *picogrids*, *nanogrids* and *microgrids*, all together.

Keywords— ***Picogrid, Nanogrid, Microgrid, Blockchain, Machine Learning, Internet of Things (IoT)***

6.1 INTRODUCTION

There are a few rationales for reducing emissions from the electricity industry: (a) by decreasing production, (b) by creating a new design model that prioritises the environment and then business, or (c) by reducing consumption. Option (a) contradicts the existing economic-political-social ecosystem today, involving radical law changes plus an international consensus; Option (b) requires a brand new infrastructure that may be only affordable by a few nations - and also requires an international consensus. Thus, options (a) and (b) are highly dependent on governmental initiatives and international consensus - ensuring that all nations would agree on taking effective actions to cut emissions; If any of those were achievable, they would have been deployed long ago. That leaves option (c) as the only alternative, where individuals take the leadership role to reduce consumption and lower emissions.

In the pursuit of individuals taking accountability for lowering global emissions, there must change in habits, behaviours, and beliefs, which leads to a need for re-education. Lowering emissions means lowering daily consumption, acquisitions, and infrastructure. Reducing electricity consumption is only a small part of a much larger problem. Householders might save money on electricity bills and then acquire new products with a high volume of embedded emissions – so, in the end, reducing electricity consumption is only part of history – and will not help much in lowering global emissions. The rebound effect may be worse than not having not saved energy in the first place [32, 33, 571, 572].

The classic example of the rebound effect is the fallacy of rooftop solar panels when governments spend huge sums of funds on a strategy that has not brought any contributions to lowering global emissions. It truly lowers the electricity bill to the consumer, inducing the householder to think that solar panel is helping to lower global emissions, which is far from the truth. Household energy consumption represents only 5% of the global emissions, whereas the emissions related to acquisitions of goods, services, and infrastructure is around 76% [351, 352]. So, the government tackles the small side of the problem (5%), while an entire chain of producers and intermediaries attacks the other side (76%). That partially explains why global emissions keep rising almost steadily [626].

Should consumers spearhead a solution to lower global emissions, the following must be taken into consideration:

- the existing power grid releases emissions as a result of several root causes around economics, policymaking, and designing constraints;
- the existing power grid is large and centralised, which undermines competition;
- several conflicts of interest led to a deadlock between government, corporations, and society towards sustainability;
- several propositions to solve the global emissions have been fronted by developed countries and accommodated under the UN umbrella, and they all failed;

- the lack of a global consensus capable of promoting efficient mechanisms to measure, verify, and report atmospheric emissions;
- the inexistence of credible plans promoting an alternative network design and infrastructure that prioritise clean methods for the production of fossil fuels and electricity generation;
- the absence of laws and regulations to protect the environment, in opposition to the abundancy of tragedy-inducing legislation that stimulates emissions;

As a result of monopoly and state control, people are forced to use a system that has become the largest source of GHG emissions on Earth [422, 488]. So, a new electricity infrastructure must be in place so people can have choices. The new system should support clean production methods and, in the meantime, raise consumer awareness to avoid the rebound effect, e.g., lower consumerism and unnecessary acquisitions. The BAIoTAG framework, supported by the ADCx model and BAIoT system, has been conceived to fill this gap [682, 638, 683].

The ADCx model uses small and decentralised DC power grids, enabling a circular economy and healthy competition among neighbourhoods. It prioritises sustainability and autonomy, with total isolation from the AC grid. Under the ADCx model, each prosumer unit is named a picogrid. Prosumer refers to any site (e.g., a house or unit) capable of producing, storing, and consuming electricity. A *nanogrid* refers to a group of interconnected picogrids, and it can be dozens of houses within a street block, a community, a condominium, or a multi-unit building. For last, a *microgrid* interconnects several *Nanogrids,* and its coverage area can reach an entire suburb with several thousand houses.

The BAIoT system [683] supports the ADCx model by enabling integration among the many subsystems. It establishes reliable communication between agents, enabling automation, intelligence, analytics, and educational feedback. Blockchain, IoT and Artificial Intelligence (BAIoT) can work together, complementing each other, to enable individuals and organisations to reach sustainability faster. While ADCx delivers the power infrastructure that encourages clean methods and autonomy, helping to establish user accountability and lower emissions, the BAIoT system enables mechanisms to optimise resources, automate tasks, and, in the meantime, demotivate irrational consumption, running analytics and sending educational feedback to raise consumer awareness.

The BAIoTAG framework brings the ADCx-BAIoT concepts together within a more controlled environment. It enables users to control their CO2 footprint, educate themselves, improve habits, share information with peers, and reach sustainability. The BAIoTAG framework establishes the 12 foundational principles that tackle the seven root causes of global emissions. The BAIoTAG framework boldly assumes the limitations, conflict of interests, and the inability of current power brokers to reduce global emissions. It addresses all the roadblocks, the monopoly problem, the need for new infrastructure, and ample supporting mechanisms for the user. The user must have various tools to quantify, mitigate, raise awareness, and become motivated to reach sustainability. BAIoTAG offers a new pathway for prosumers to break free from a system that pollutes and depletes the planet.

6.2 THE OBJECTIVE OF THE EXPERIMENT

Unlike traditional power systems where consumers benefit from 24x7 electricity availability, an autonomous power plant has limited resources and power instability due to the stochastic nature of the small-scale power supply. This ongoing quest for an autonomous solution requires a permanent supervisory system. Depending on the topology, it may count on the neighbours to mitigate its energy needs, even though power and load forecasting are mandatory.

The purpose of running continuous analyses on power demand and generation is to obtain meaningful knowledge from the user and power supply profile. While IoT collects and organises the data in a time-series-based format, Machine Learning (ML) models run analytics to make predictions, identify patterns, detect anomalies, and provide educational feedback to the user. The continuous quest for a small power plant for electricity distribution is to forecast energy consumption and supply, anticipate events, and provide mitigation options.

This experiment aims to examine the suitability of deploying ML algorithms in several cases and determine which ones presented better outcomes in terms of accuracy.

6.3 METHODOLOGY

The first challenge was to decide whether the research should rely on the data acquired locally for a single house versus the possibility of using external data. Both options were considered and tested. However, the option with a house presented limitations since nanogrid and microgrids depend on a large amount of data (years) and many houses (dozens at least). While installing sensors, collecting local data for a limited period (e.g., three months) via energy management systems, and cleaning and running the transformations were important to prove the IoT automation aspects, it turned out to be less beneficial to conduct ML analyses.

On the other hand, a larger dataset with many houses, externally acquired, with a significant amount of reliable data collected over the years, would bring many advantages. That was the selected choice to address the research questions.

6.3.1 DATA LIBRARY SELECTION

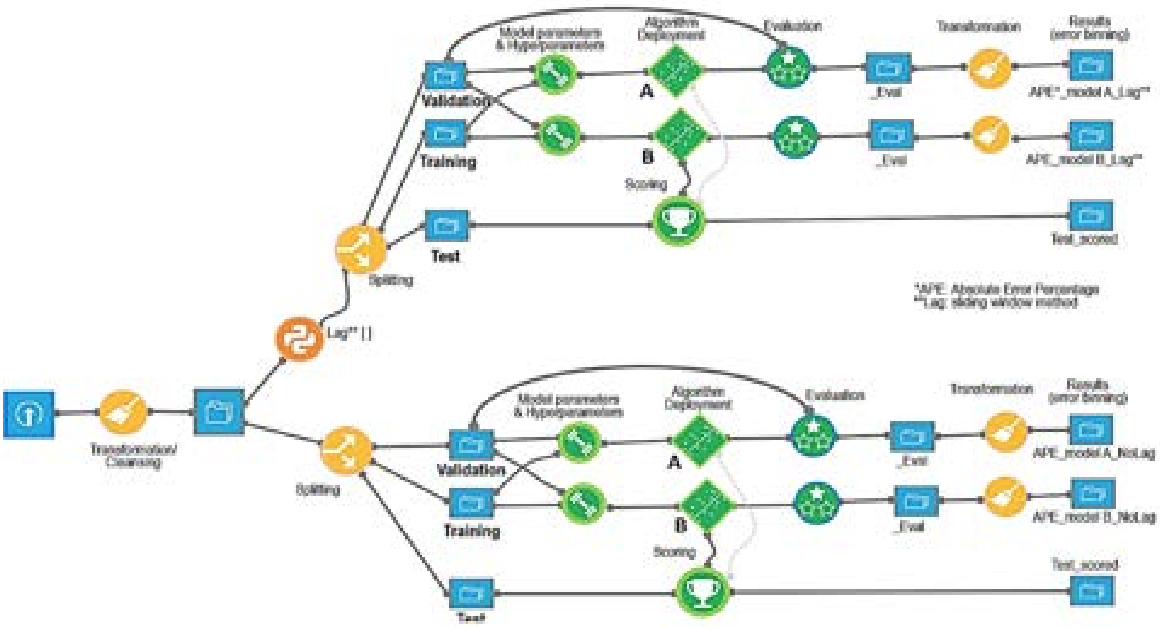


Figure 89: Overall methodology for Machine Learning deployment DSS tool

Power load disaggregation via non-intrusive methods (or NILM) refers to the process of using signal processing and machine learning to separate the energy consumption of a building into individual appliances [557]. In recent years, several data sets have been released to provide reliable disaggregated data for power appliances and buildings. Among the most well-known datasets are:s Enertalk [339] (Korea), DRED [340] (Netherlands), REDD [341] (USA), REFIT [342] (UK) and Dataport [343] (USA). Some of these data libraries only cover a limited number of houses, have a limited period, or have a low number of appliances, making them unsuitable for this particular study. For these reasons, Dataport libraries have been selected since hundreds of research studies have already been published based on these datasets.

Historical power consumption data, metadata reports, and data dictionaries have been obtained from Dataport data libraries via a user license agreement between Pecan Street Inc and registered university students [684]. Austin, Texas-based Pecan Street Inc. research group has been collecting power consumption data for over six years, including 1,115 homes and businesses [685] and making it available for registered customers, including many universities worldwide.

In total, assorted data for 73 houses have been acquired during the periods of 2014 and 2019: 25 houses in Austin (Texas) collected in 2018, 25 in upstate New York between May October 2019, and 23 houses in California in varied periods, between 2014 and 2018 (See Figure 90, and Table 9). All data is anonymised from volunteer participants. The frequency of data collection includes 15 minutes, 1-Minute and 1-second intervals. Metadata containing climate data and site details (e.g., house size, location) were combined with the consumption data. The following table summarises the whole set of data collected by Dataport Pecan Street:

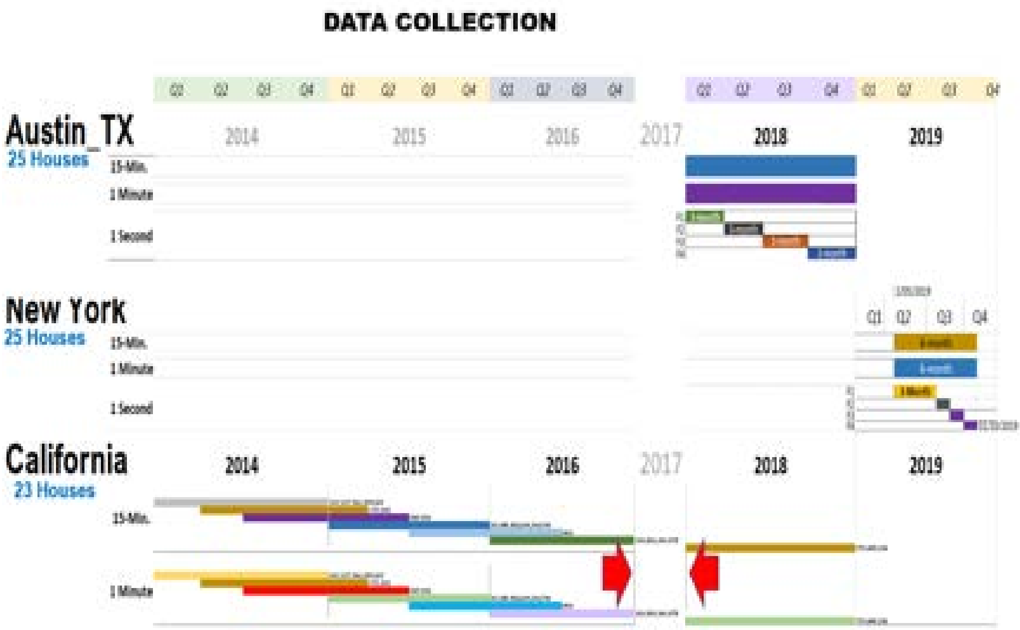


Figure 90: Data collected by Pecan Street from Texas, New York, and Califorina between 2014 and 2019

	Interval / Frequency	Nr. Houses	Period	Year
Texas	1-Sec, 1-Min, 15-Minutes	25	1 year	2018
New York	1-Sec, 1-Min, 15-Minutes	25	6 months	2019
California	1-Sec, 1-Min, 15-Minutes	23	1 year	2014-2018

Table 9: Dataport datasets download summary

6.3.2. DEFINING AND SELECTING THE CASES

From a practical standpoint, it is important to streamline what cases would provide the most significant outcome when considering data sizes, frequency collection, computational cost, timing, and accuracy. From a total of 18 scenarios, only six cases have been considered as follows:

- Case 1: A *microgrid* with 73 houses and data collection at a 15-minute interval
- Case 2: A *nanogrid* with 25 houses and data collection at a 15-minute interval
- Case 3: A *nanogrid* with 25 houses and data collection at a 1-minute interval
- Case 4: A *picogrid* (house) and data collection at a 15-minute interval
- Case 5: A *picogrid* (house) and data collection at a 1-minute interval
- Case 6: A *picogrid* (house) and data collection at a 1-second minutes interval

The following sections address each case; the results are presented and further discussed.

6.3.3. AI/ML TOOL SELECTION

Data Science Studio (DSS) is a predictive modelling tool commercialised by Dataiku and has been selected for this study [686]. It is a platform that bridges the need of data scientists, data engineers, business analysts, and AI consumers. Dataiku DSS tries to span the machine learning process from end to end, i.e. from data preparation through operations and application support. For this study, the DSS computation engine has been installed in a couple of Linux machines running Ubuntu (version 20.04) environment. It supports the decision-making process for the BAIoT over ADCx models and the BAIoTAG framework in running predictive modelling for each of the 6 case studies.

All time-series datasets related to this experiment contain labelled data. Since predictive analyses are the main goal, it implies that a supervised learning model is required. The method involves collecting historical consumption data and using it to predict future demand and power requirements. All the inputs & outputs are numeric values, and other variables include temperature, house sizes, and location. DSS offers a variety of embedded algorithms for predictive tasks, and the user may tailor or bring extra systems to incorporate into the model.

6.3.4. Data Cleansing & Preparation

Fourteen time-series datasets (Table 10) with power consumption data have been extracted from the Dataport library [684], with 79 columns, including several appliance types, solar photovoltaic power, electrical vehicles data, and house ID. Data transformations, merging, parsing, wrangling, and cleaning were performed, and outliers and inconsistences were removed. After cleaning, merging metadata and all data transformation in place, it was possible a reduction from 79 columns originally down to 25 columns. This procedure was applied to all the datasets.

		Freq.	File_Name	CSV File Size	Number of Rows	Collection Period	
Austin	1	15min	Austin_15Min	153 Mb	873,286	1/01/2018	31/12/2018
	2	1min	Austin_1Min	2.45 Gb	13,100,539	1/01/2018	31/12/2018
	3	1sec	Austin-F1	37.52 Gb	193,384,800	1/01/2018	31/03/2018
	4		Austin-F2	38.13 Gb	196,556,400	1/04/2018	31/06/2018
	5		Austin-F3	38.21 Gb	196,815,608	1/07/2018	30/09/2018
	6		Austin-F4	38.43 Gb	196,815,608	1/10/2018	31/12/2018
New York	7	15min	NY_15Min	72.78 Mb	441,599	1/05/2019	31/10/2019
	8	1min	NY_1Min	1.09 Gb	6,624,000	1/05/2019	31/10/2019
	9	1sec	NY_F1	32.93 GB	198,719,996	1/05/2019	31/07/2019
	10		NY_F2	11.11 Gb	66,938,400	1/08/2019	31/08/2019
	11		NY_F3	10.75 Gb	64,789,174	1/09/2019	30/09/2019
	12		NY_F4	11,12 Gb	66,959,998	1/10/2019	31/10/2019
California	13	15min	Calif_15Min	135 Mb	805,524	Depends on the house ~2014 - ~2019	~2014 - ~2019
	14	1min	Calif_1Min	1.76 Gb	12,084,183	Depends on the house ~2014 - ~2019	~2014 - ~2019
		Total:		223.5 GB	1214909115	Rows x 79 Columns	

Table 10: Total 14 datasets - file sizes, number of rows, collection period

6.3.5. USE CATEGORISATION & FEMTOGRIDS

Power use categorisation is critical to the BAIoTAG framework since it allows grained analyses on a circuit basis. It enables better performance in predicting consumption behaviour and accuracy. Disaggregating data facilitates pattern recognition, faster diagnosis, tailored feedback, and more energy savings. Besides, it facilitates monitoring, fault isolation, and management.

Within the ADCx model, a *femtogrid* is an electrical circuit serving one or more power loads under the same use category. It includes cables, circuit breakers, outlets, protective gears, earthing, connectors, and termination frames. The nine use categories for *femtogrids* under the ADCx model are: (a) lighting, (b) food preservation, (c) cooking and water heating, (d) labour-saving and mechanical tools, (e) education, communication, gaming, (f) space cooling and heating, (g) hygiene, (h) outdoor entertainment and (j) electric vehicles. The raw data acquired from Dataport were grouped, and categorised, matching each *femtogrid*.

6.3.6. TARGET VARIABLE & FEATURE SELECTION

The target variable of a dataset is the key feature the model wants to gain a deeper understanding of. The total consumption for all appliance categories (A through G) has been chosen as this experiment's target variable (Figure 91). It includes lights, refrigerators, cooking appliances, labour-saving machines, air-conditioners, heaters, and more. Seeking consistency across all scenarios, only features that impacted results the most were selected. A supervised machine learning algorithm uses the historical data to learn patterns and uncover relationships between the target variable and all the other variables (features).

FEATURE HANDLING		STATUS
#dataID	House identifier (Picogrid #)	Rejected, too many equal values
#localminute	Original Timestamp	Reject
#localminute_Parsed	Parsed Timestamp (ISO 8601)	Reject
#date	DD/MM/YYYY	Reject
#time	HH:MM:SS am/pm	Reject
#day_since_started	Days counted since project started	Reject
#app_Total_A_B_C_D_E_F_G	Total Consumption All Femtogrids	TARGET VARIABLE
#lights_A	Consumption sum for all the lights	
#food_preserv_B	Consumption Sum for fridges, freezers, coolers	
#cooking_C	Consumption Sum of all kitchen applicancs	
#mechanical_labor_sav_D	Sum of all mech labor appl.	
#Space_cooling_heating_F	Sum of all air-conditioners/heating un	
#higiene_G	Consumption Sum of all bathrooms	
#electrical_vehicle_J	Consumption Sum of all electr. Vehicles	Rejected, too many equal values
#renewable_energy	Sum of power generation for renewables	
#grid	Power from utility service provider	Reject
#TAVG_C (temp avg Celsius)	Average Temperature in Celsius	
#TMAX_C	Maxima Temperature in Celsius	
#TMIN_C	Minimum Temperature in Celsius	
#building_type	Type of building (house, flat, etc.)	Rejected, too many equal values
#city	City area where house is located	Rejected, too many equal values
#LAT	Latitude	Rejected, too many equal values
#LONG	Longitude	Rejected, too many equal values
#house_constr_year	House Construction Year	
#total_SQMT	House size in square meters (SQMT)	

Figure 91: Target Variable & Feature Selection

6.3.7. Algorithms Selection

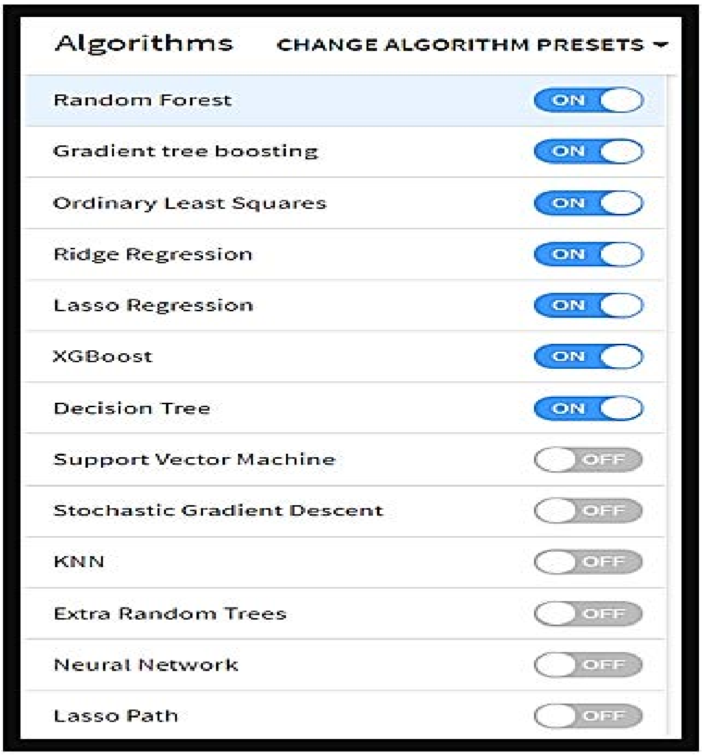


Figure 92: Algorithm selection

The task involved is prediction, and the target variable is a numeric value. Many algorithms can perform such tasks. Among the most popular are the Ramdon Forest, Gradient Tree Boosting (GBT), Ordinary Least Square (OLS), Ridge Regression, Lasso Regression, XGBoost, and Support Vector Machine. Random Forest is a powerful ensemble algorithm, highly used for classification, regression and other tasks. It builds decision trees during the phase of training. It uses bagging (or bootstrap aggregation) and emphasizes randomness when building each individual tree to create an uncorrelated forest of trees. XGBoost is a highly scalable and accurate algorithm, a spinoff of gradient boosting implementation that improves computation power, improves generalisation, and saves time and resources. Figure 92 shows some of these algorithms selected for the experiment.

6.3.8. Error Metrics

Metrics are often used in conjunction with scenarios, depending on dataset sizes, the number of rows, and columns. Mean Absolute Error (MAE) has been selected as the preferred method for error metrics since outliers do not severely impact it. However, RMSE (Root Mean Square Error) has also been used for comparison reasons.

6.3.9. Model Hyperparameters

The Hyperparameter settings define how the DSS engine searches and define the best strategies, e.g., grid, random or Bayesian searches. During the hyperparameters optimisation phase, each set of hyperparameters will consider all the selected algorithms and cross-reference with the metrics established (MAE, in this case). In this experiment, a grid search has been selected. The metrics used to rank hyperparameter points are computed by cross-validation, and 5-fold cross-validation has been selected. In K-fold cross-validation, the dataset is partitioned into k equally sized subsets. The process is then repeated k times, once for each fold defined by the subset used as a validation set. (Figure 93).

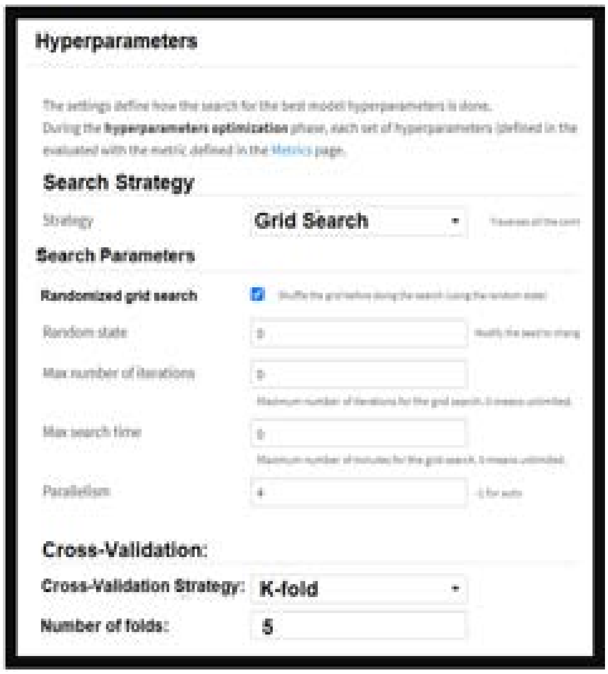


Figure 93: Hyperparameters

6.3.10. TRAIN / TEST SET FOR FINAL EVALUATION

The train/test split policy used in the DSS tool was '*explicit extracts from two datasets*', one for training and one for test. For the dataset for the picogrids @ 1-sec intervals, the number of records was very large (e.g., 15-million rows), and then the sampling method was used. In both sets, train and test, random sampling with a ratio of 20% was selected. As for the datasets with lower than 2 million rows, it was chosen to train the whole dataset and no sampling (Figure 94).

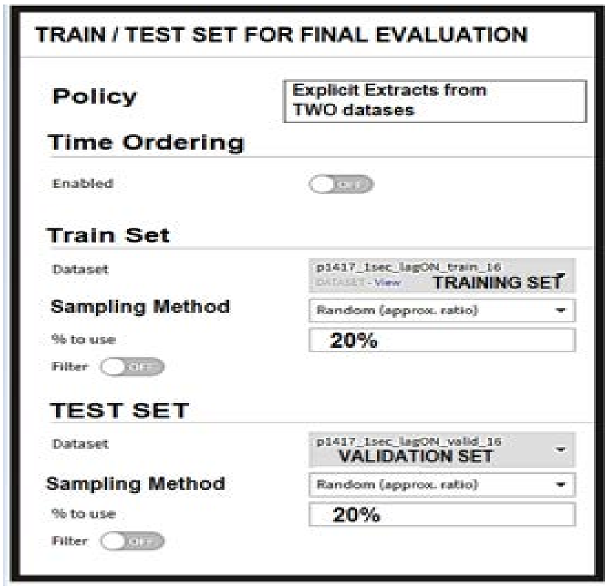


Figure 94: Train / Test settings for > 2million rows

6.4 RESULTS

The results for each case are now presented, as per as listed in section 6.3.2. The lag function (sliding window) has been considered across all cases to ensure consistency. Then, for each scenario, only two algorithms were compared: Random Forest and XGBoost.

6.4.1 CASE 1: MICROGRID MODELLING @ 15-MINUTE INTERVAL DATA COLLECTION

A *microgrid* refers to a (a) site facility equipped with power sources and storage systems, (b) a coverage area serving many affiliated *nanogrids*, (c) a network system integrating communication and power devices under a unified platform, or (d) a legal organisation such as association or cooperative formed by the network participants.

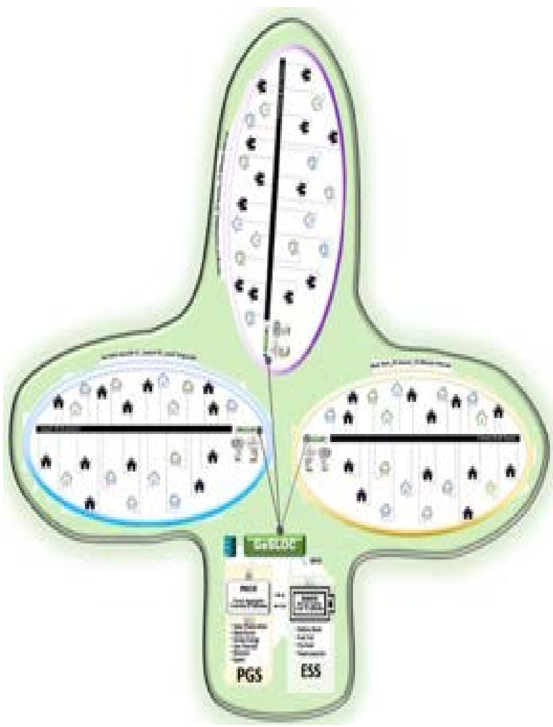


Figure 95: : A microgrid with 3 nanogrids and 73 picogrids

In this experiment, a *microgrid* with 73 houses has been modelled. Real consumption data has been acquired from Dataport libraries. Data from upstate New York, Texas and California have been grouped from distinct datasets and adjusted to the same timeline. For instance, the data from New York upstate was collected in 2019 and shifted to 2018. The same for California, as data collection took place between 2014-2018; however, the entire dataset was adjusted to 2018. Since the goal was to model the consumption behaviour for a large group of houses, weekdays, months, and daily timing, the above-mentioned adjustment did not impact the overall consumption patterns and suited the purpose of the experiment.

The *microgrid* dataset had 2,120,402 rows and 28 columns. Data has been split into training (78%), validation (18%) and test (4%) subsets. Four tests were conducted in a *microgrid* representing two scenarios, with and without lag function. In both scenarios, the models were trained using Random Forest and XGBoost algorithms, and the results have been depicted in Figures 96-101

Figure 96 shows the prediction results using the Random Forest algorithm without the sliding windows function (lag). Period Forecasted: 12-16 October 2018. The model returned 41% within the range of 0-5% and 23% for 5-10%, which was an acceptable output compared to the other models. Figure 101).

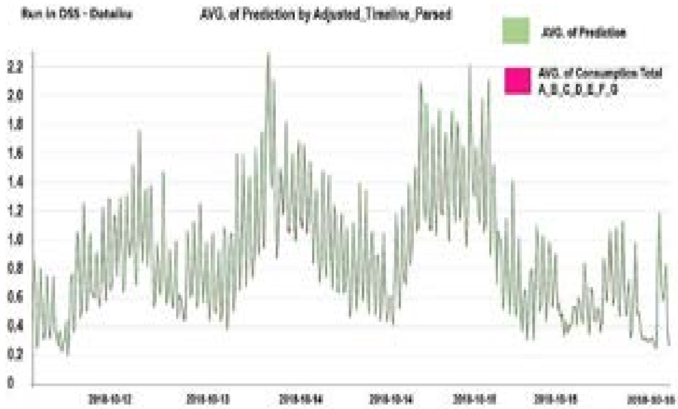


Figure 96: Case1_5 days consumption prediction without lag function and using Random Forest algorithm

Figure 97: Case1_5 days consumption prediction without lag function using XGBoost algorithm

Figure 97 shows the prediction results for all appliances for five consecutive days, using the XGBoost algorithm, without the sliding windows function (lag). Period forecasted 01-05 January 2018. The model returned 33% within the range of 0-5% and 26% for 5-10%, which was still an acceptable output (Figure 101).

Figure 98 shows the prediction results (Case 1) using the Random Forest algorithm with lag function. Period forecasted 12-17 Oct-2018. The model returned about 48% within the range of 0-5% and 21% for 5-10% and was the best performance, including seven algorithms (Figure 101).

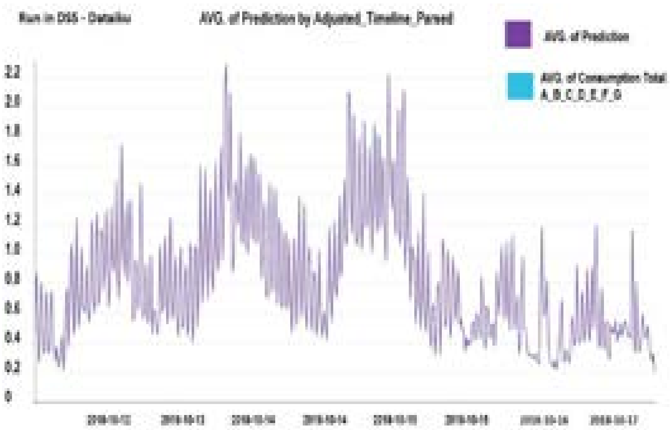


Figure 98: Case1_ 5 days consumption prediction with lag function, using Random Forest algorithm

Figure 99 shows the prediction results using the XGBoost algorithm with lag function. Period of collection 12-18 October 2018. The model returned about 46% within the range of 0-5% and 23% for 5-10% and was the second-best performance among seven algorithms (Figure 101).

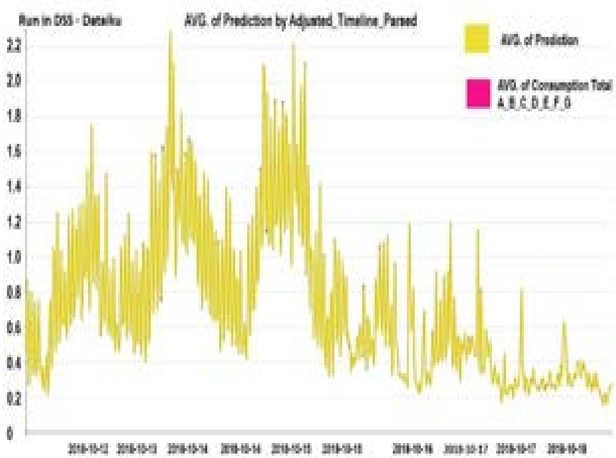


Figure 99: Case1_5 days consumption prediction with lag function, using XGBoost algorithm

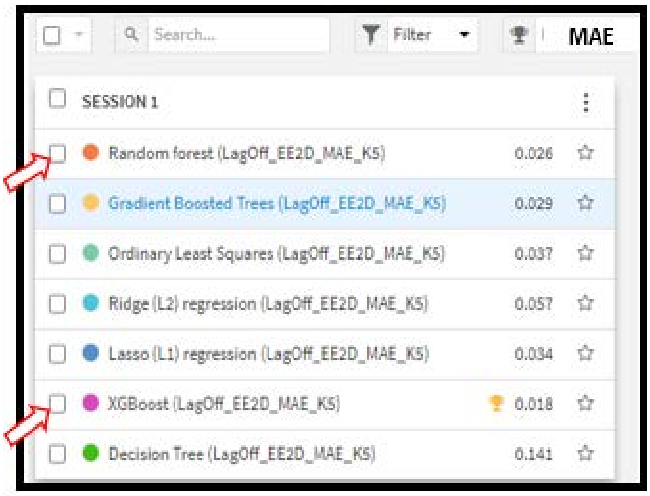


Figure 100: Case 1_Model training results (No Lag)

The output from the DSS tool showing the metrics based on Average Mean Error (MAE), for Case1-Session 1, for all the algorithms is represented in Figure 100. It can be noted that XGBboost and Random Forest performed slightly better than the other algorithms.

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The error metrics for comparing bin errors (the percentiles for Absolute Error Percentage Error - APE) for the four scenarios in Case 1 (lag vs no lag and Random Forest versus XGBoost) are shown in Figure 101. Charts a) and b) refer to the models trained without lag, and charts c) and d) refer to the models trained with lag.

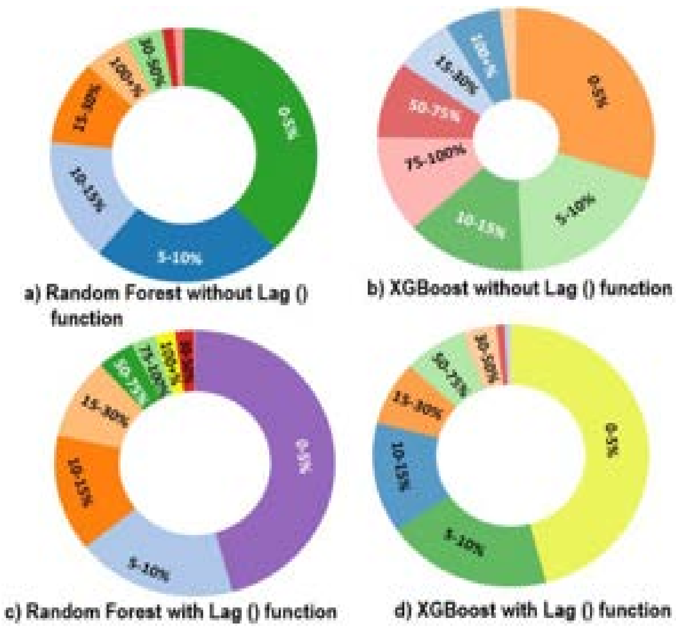


Figure 101: Case 1 metrics comparison

6.4.2 CASE 2: NANOGRID MODELLING –@15-MINUTE INTERVAL DATA COLLECTION

A *nanogrid* network integrates a collection of picogrids under a single electrical, communication and data processing platform. The building blocks of a *nanogrid* system include all the picogrids (e.g., houses, units), electrical gears for power interconnection (e.g., cables, terminations, safety apparatuses), communication devices, and operating devices system and depending on the power source or storage systems. The *nanogrid* system enables the peers to communicate, exchange private data, and trade electricity locally or via a *microgrid* operator. An autonomous DC *nanogrid* aggregates power sources under a common DC bus, as depicted in Figure 102.

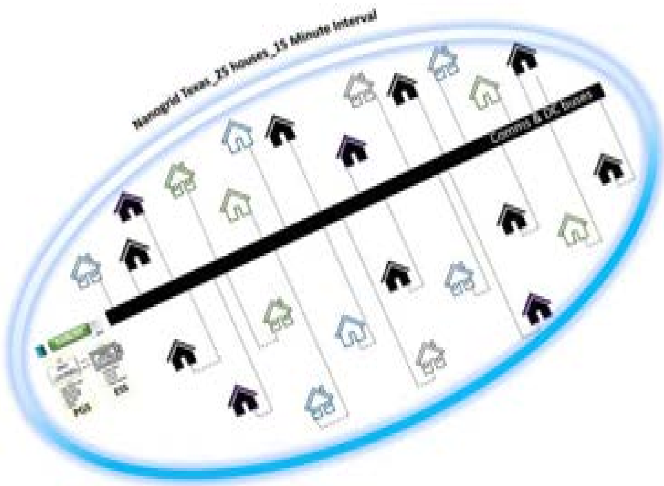


Figure 102: Modelling a nanogrid network with 25 houses

The *nanogrid* dataset had 873,279 rows and have been split into training (78%), validation (18%) and Test (4%) dataset. The test dataset represented about five days of consumption data. Four tests were conducted in a *nanogrid* representing two scenarios, with and without lag function. In both scenarios, the models were trained using several algorithms. The results for Random Forest and XGBoost algorithms are depicted in figures 103-108.

Figure 103: Case 2_3-week prediction without lag function, using Random Forest algorithm

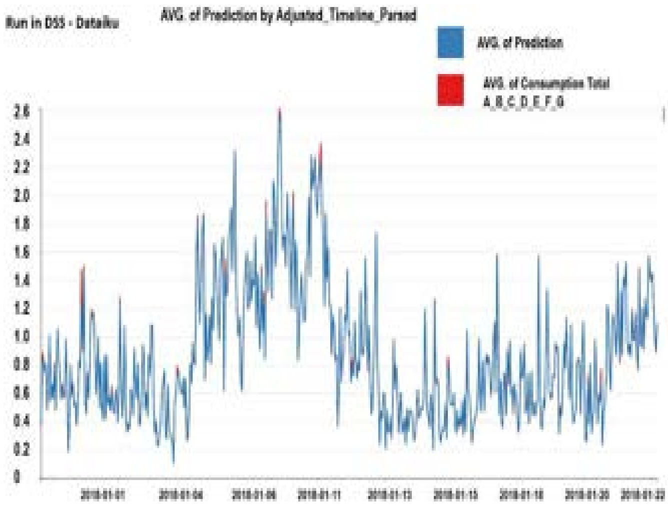


Figure 103 shows the prediction results (Case 2) using the Random Forest algorithm without window sliding (lag function). Period 01-22 Jan 2018. The model returned 34% within the range of 0-5% and 17% for 5-10% (Figure 108).

Figure 104 shows the prediction results using the XGBoost algorithm without lag function. Period 04-17 Jan 2018. The result returned 41% within the range of 0-5% and 19% for 5-10% (Figure 108).

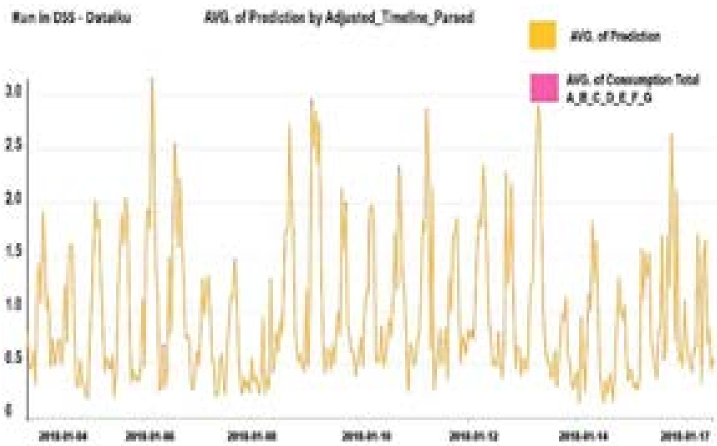


Figure 104: Case2_ 2-week prediction without lag function, using Random Forest

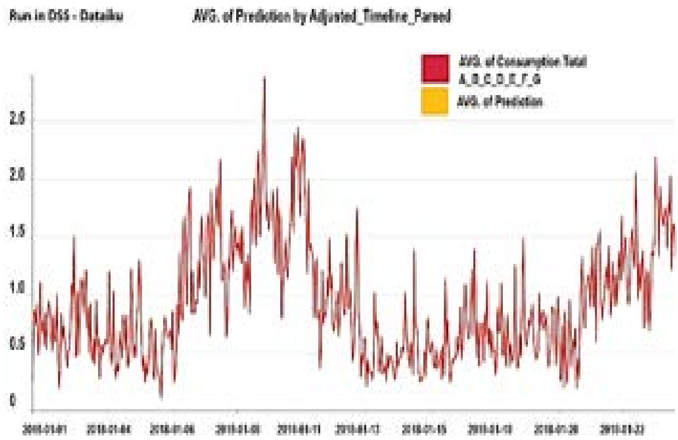


Figure 105: Case 2_3-week prediction with lag function, using Random Forest

Figure 105 shows the prediction results (Case 2) using the Random Forest algorithm with lag function. Period 01-22 Jan 2018. The model returned 53% within the range of 0-5% and 20% for 5-10%, which was the best result among all the algorithms(Figure 108).

Figure 106 shows the prediction results using the XGBoost algorithm with lag function. Period 04-17 Jan 2018. The model returned 53% within the range of 0-5% and 19% for 5-10%, which was the second-best result among all the algorithms(Figure 108).

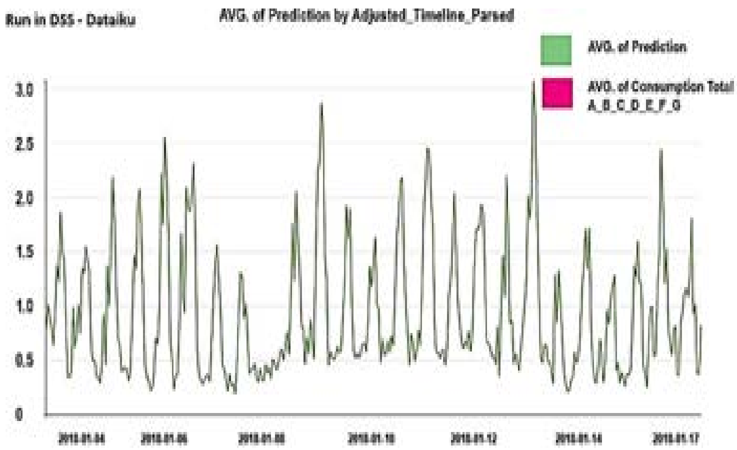


Figure 106: Case2_ 2-week prediction with lag function, using XGBoost

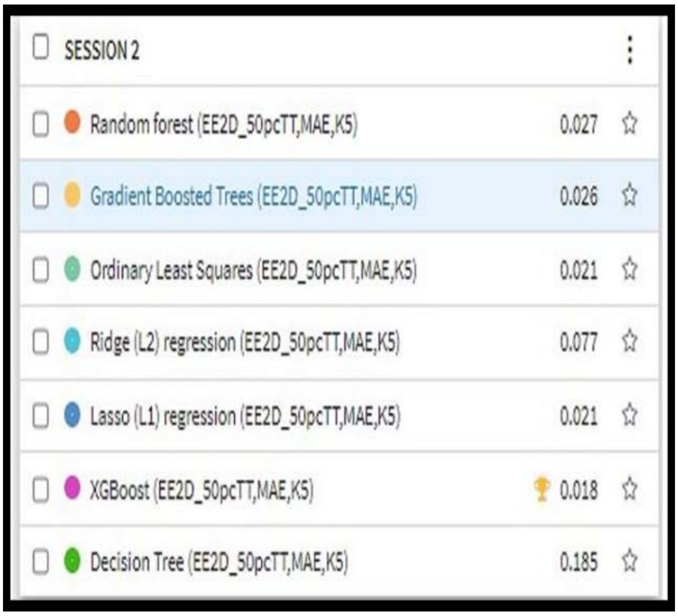


Figure 107: Case 2 Model training results (No Lag)

The snapshot (output) from the DSS tool showing the metrics results, considering the Mean Average Error (MAE), for case2-Session2, for all the algorithms are represented in Figure 107. It can be noted that XGBboost and Random Forest performed slightly better than the other algorithms.

Figure 108 shows the bin error metrics for comparing bin errors (the Absolute Error Percentage Error - APE) for the four scenarios in Case 2 (lag vs no lag and Random Forest versus XGBoost). Charts a) and b) refer to the models trained without lag, and charts c) and d) refer to the models trained with lag. For charts a) and, c) Random Forest were used, while Charts b) and d) XGBoost were used.

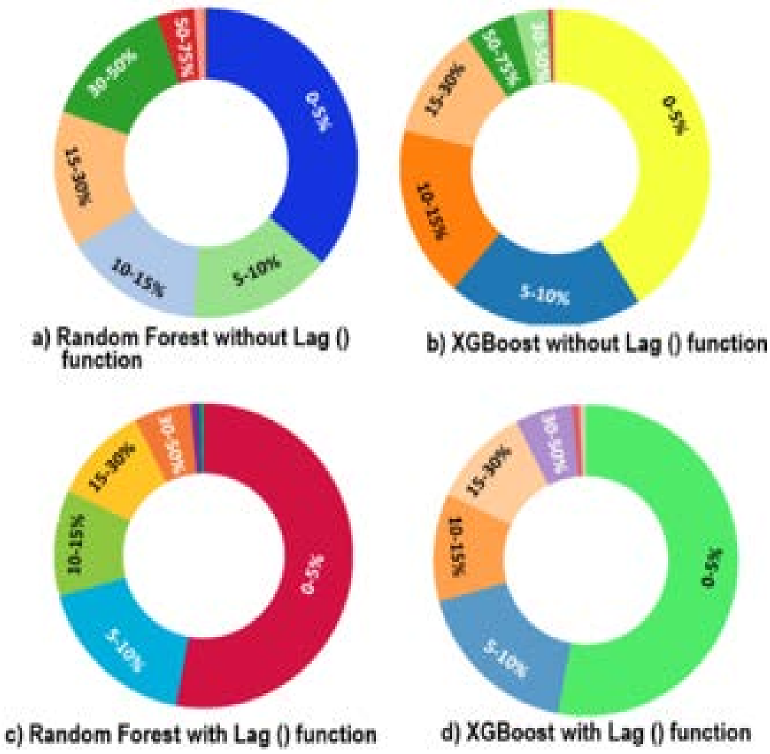
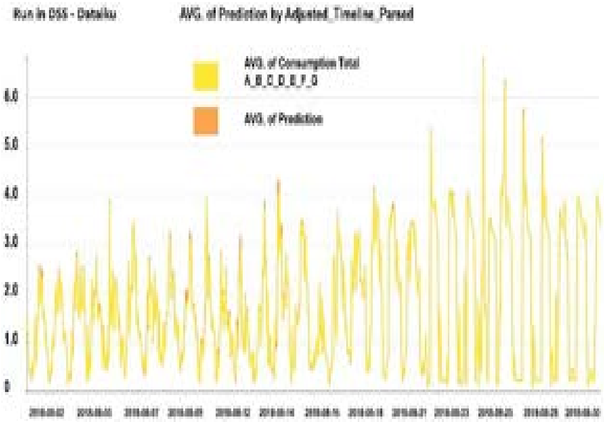


Figure 108: Case 2 Metrics comparison

6.4.3 CASE 3: NANOGRID MODELLING @ 1 MINUTE INTERVAL DATA COLLECTION

Figure 109 shows the prediction results (Case 3) using the XGBoost algorithm without lag function. Period 02-30 Aug 2018. The model returned 53% within the range of 0-5% and 19% for 5-10%, which was the second-best result among all the algorithms(Figure 114).



re 109: Case3_ 1 month consumption prediction with lag function, using XGBoost algorithm

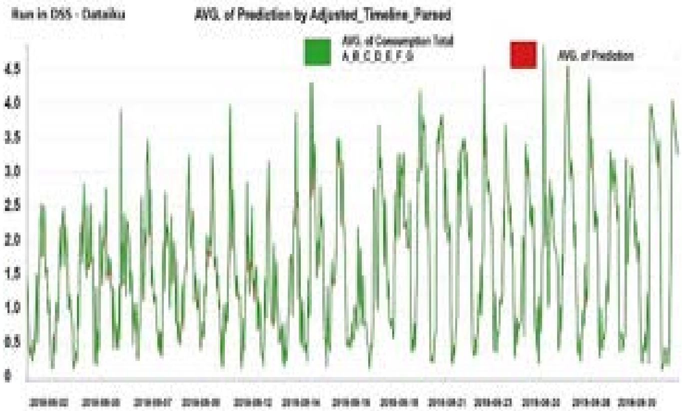


Figure 110: Case3_ 1 month prediction with lag function, using Random Forest algorithm

Figure 110 shows the prediction results using the Random Forest algorithm with sliding windows function. Period: 20-30 Aug 2018. The model returned 48% within the range of 0-5% and 13% for 5-10%, which was the best result among all the algorithms(Figure 114).

Figure 111 shows the prediction results (Case 3: 1-Minute) using the XGBoost algorithm without the sliding windows function. Period: 20-30 Aug 2018. The model returned 46% within the range of 0-5% and 13% for 5-10% (Figure 114).

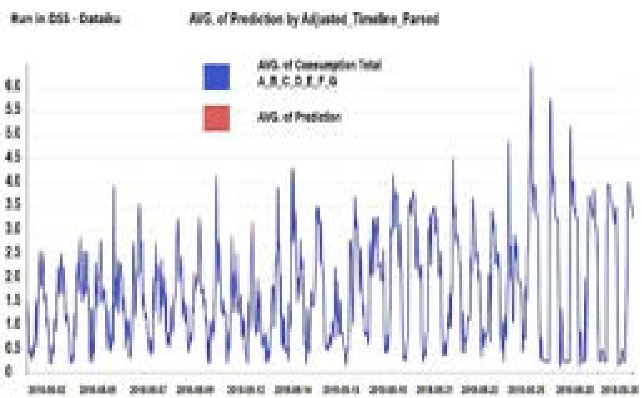


Figure 111: Case3_ 1 month prediction without lag function,, using XGBoost algorithm

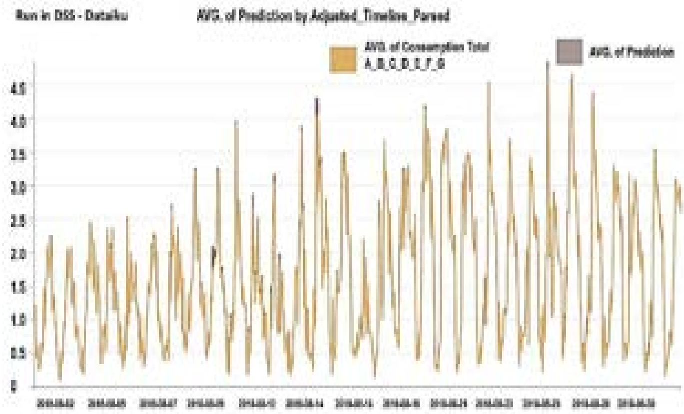


Figure 112: Case3_ 1 month consumption prediction without lag function, ,Random Forest algorithm

Figure 112 shows the prediction results using the XGBoost algorithm without sliding windows. Period: 20-30 Aug 2018. The model returned 45% within the range of 0-5% and 15% for 5-10% (Figure 114).

Figure 113 is a snapshot from the DSS tool showing the metrics results, considering the Mean Average Error (MAE) for case3-Session1, for all the algorithms, which are represented in figure 23. It can be noted that Random Forest performed slightly better than the other algorithms.

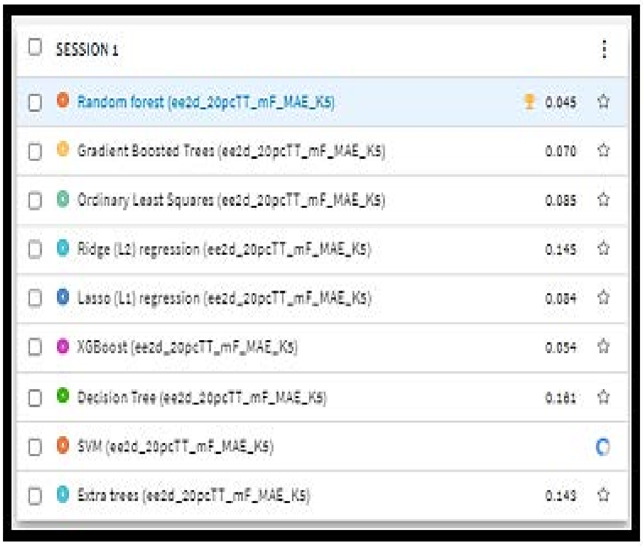


Figure 113: Case 3 Model training results (No Lag)

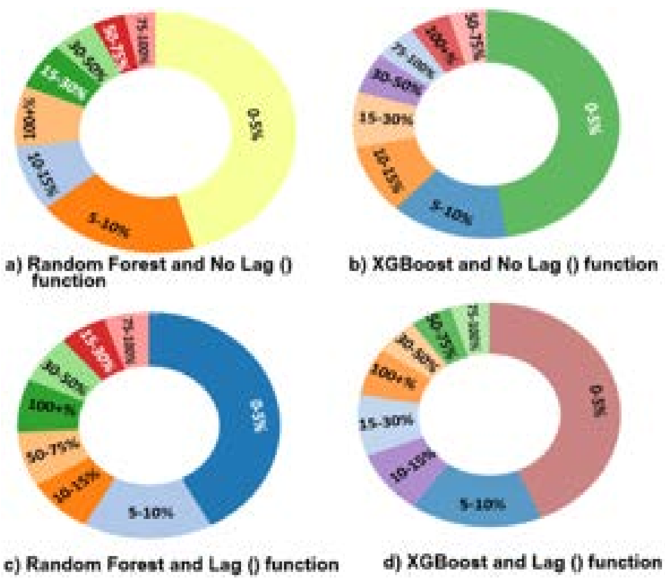


Figure 114: Case 3_metrics comparison

Figure 114 shows the error metrics for comparing bin errors (the percentiles for Absolute Error Percentage Error - APE) for the four scenarios in Case 3 (lag vs no lag and Random Forest versus XGBoost). Charts a) and b) refer to the models trained without lag, and charts c) and d) refer to the models trained with lag. For charts a) and c) Random Forest was used, while Charts b) and d) XGBoost were used.

6.4.4 CASE 4: PICOGRID MODELLING – 15-MINUTE INTERVAL DATA COLLECTION

A *picogrid* is the smallest power system within the ADCx model. This experiment refers to a standalone house (ID #1417) located in the region of Ithaca, upstate New York, US. For comparison reasons, three scenarios were considered. Firstly, a 15.3 million records dataset was used for a 1-second interval, then a 264,960 rows dataset for the 1-minute interval, and thirdly, a dataset with 17,664 rows for a 15-minute interval. Data from *picogrid* #1417 has been acquired from Dataport Pecan Street library [684] on 01-May-2019 and 30-October-2019.

Figure 115 shows the prediction results using the XGBoost algorithm without lag function. (Case 4: 15-min interval). Period: 01 May to 31 Oct 2018. The model returned 38% within the range of 0-5% and 21% for 5-10% (Figure 120)

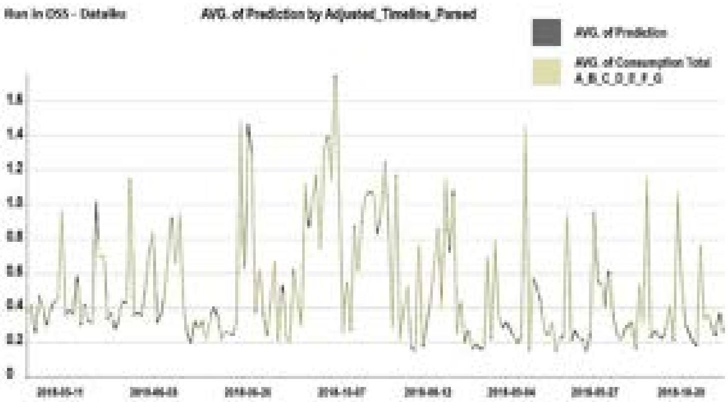


Figure 115: Case4_ 15-minute consumption prediction without lag function, using XGBoost algorithm

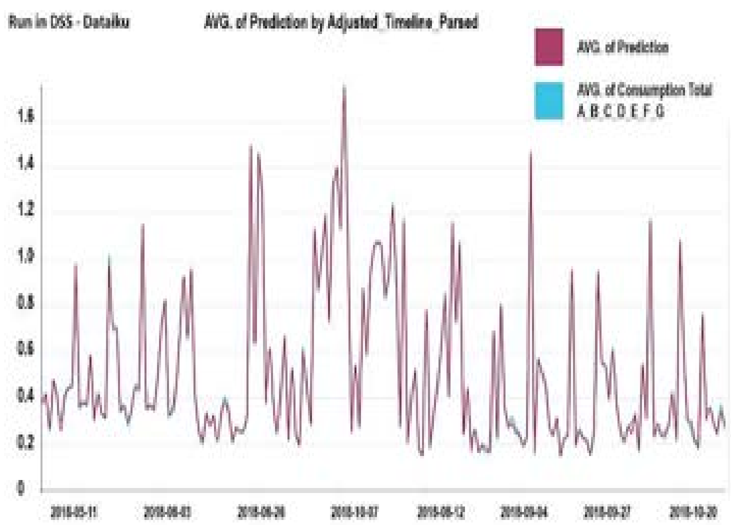


Figure 116: Case4_ 1-week consumption prediction without lag function, using Random Forest algorithm

Figure 116 shows the prediction results using Random Forest algorithm without lag function. (Case 4: 15-min interval). Period: 01 May to 31 Oct 2018. The model returned 41% within the range of 0-5% and 21% for 5-10%, which was the -best result among all the algorithms (Figure 120).

Figure 117 shows the prediction results (Case 4) using the XGBoost algorithm with lag function. (Case 4: 15-min interval). Period: 01 May to 31 Oct 2018. The model returned 39% within the range of 0-5% and 21% for 5-10%, which was the second-best result among all the algorithms (Figure 120).

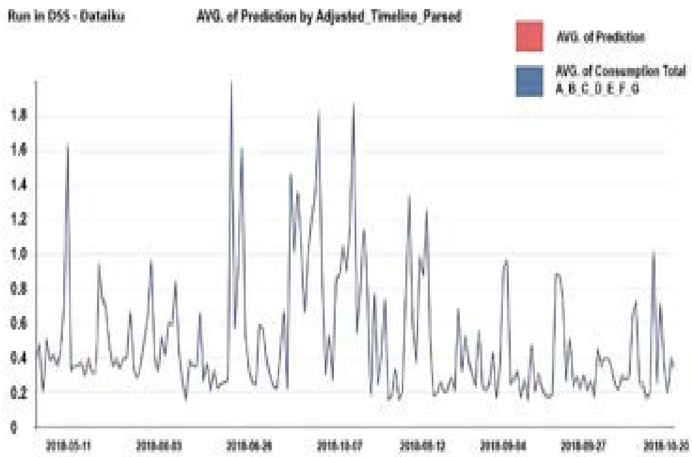


Figure 118: Case4_ 1-week consumption prediction with lag function, XGBoost algorithm

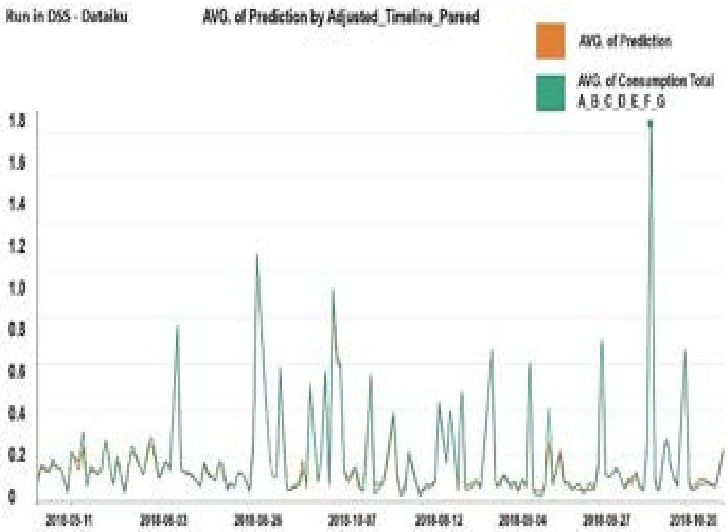


Figure 117: Case4_ 1-week consumption prediction with Lag function, using Random Forest algorithm

Figure 118 shows the prediction results using the Random Forest algorithm with sliding windows function. (Case 4: 15-min interval). Period: 01 May to 31 Oct 2018. The model returned 41% within the range of 0-5% and 18% for 5-10% (Figure 120).

The snapshot from the DSS tool showing the metrics results, considering the Mean Average Error (MAE), for case 4-Session1, for all the algorithms are represented in figure 119. It can be noted that XGBboost and Random Forest performed slightly better than the other algorithms.

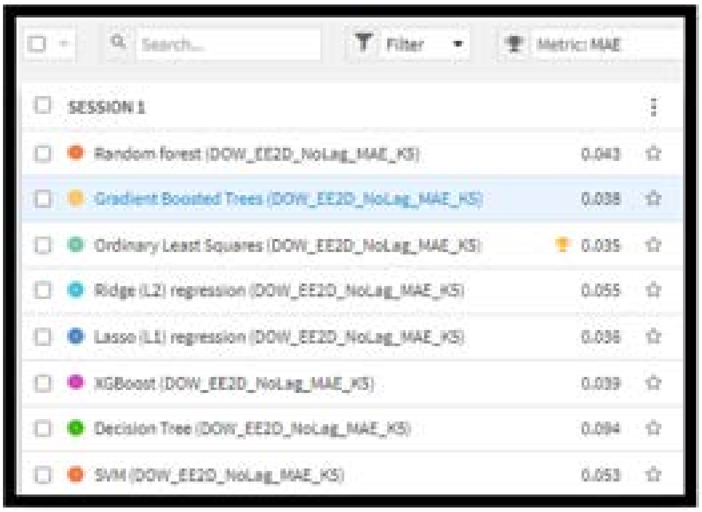


Figure 119: Case 4_model training results

Figure 120 shows the error metrics for comparing bin errors (the percentiles for Absolute Error Percentage Error - APE) for the four scenarios for Case 4: (15-min interval). It compares lag vs no lag and Random Forest versus XGBoost algorithms. Charts a) and b) refer to the models trained without lag, and charts c) and d) refer to the models trained with lag. For charts a) and c) Random Forest was used, while Charts b) and d) XGBoost were used.

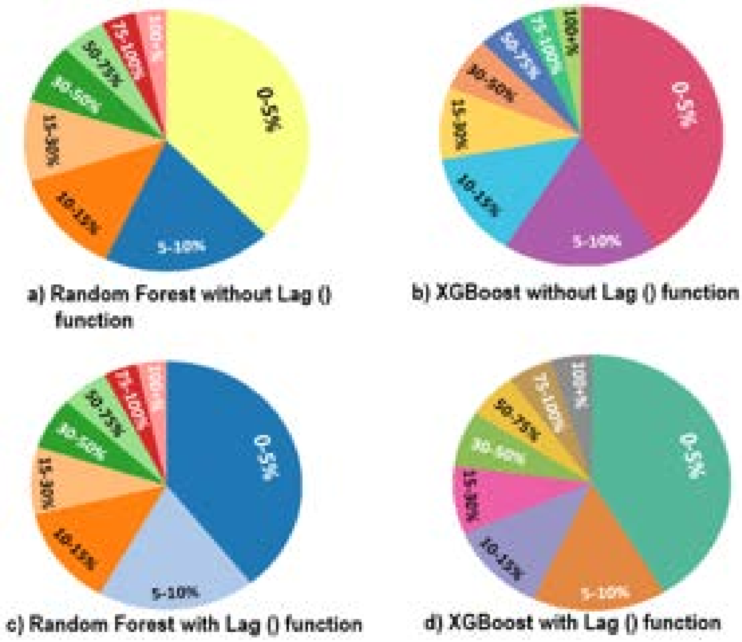


Figure 120: Case 4, metrics

6.4.5 CASE 5 PICOGRID MODELLING @ 1-MINUTE INTERVAL

Figure 121 shows the prediction results case 5, 1-minute picogrid, the Random Forest algorithm without lag function. Period: 01 May to 31 Oct 2018. The model returned 19% within the range of 0-5% and 9% for 5-10% (Figure 126). Many attempts have been tried; however, the model did not perform satisfactorily.

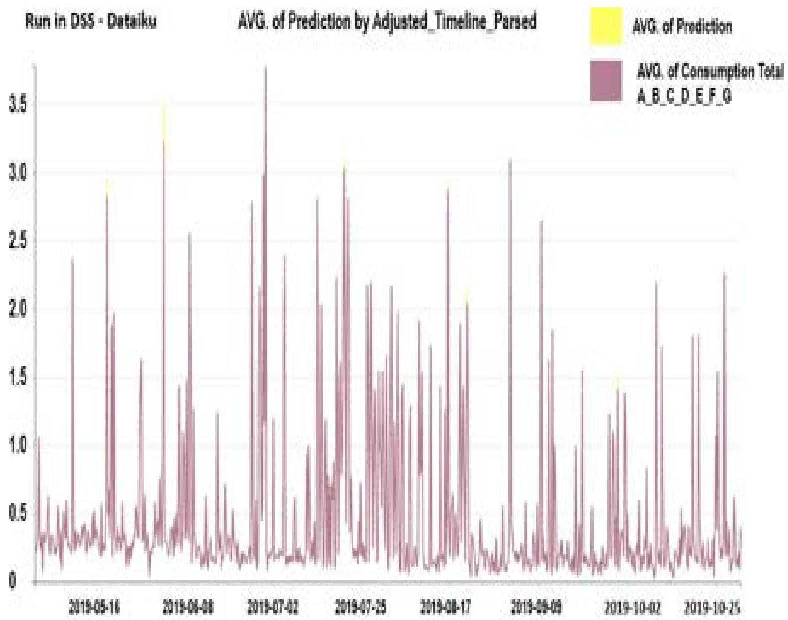


Figure 121: Case5_ 6-month consumption profile without lag function, using Random Forest algorithm

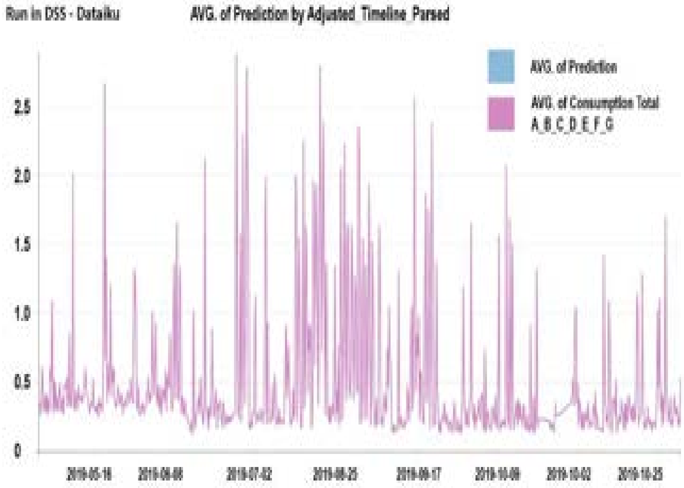


Figure 122: Case5_ 6-month consumption profile without lag function, using XGBoost algorithm

Figure 122 shows the prediction results using the XGBoost algorithm without lag function. Period: 01 May to 31 Oct 2018. The model returned 38% within the range of 0-5% and 28% for 5-10% and was the best performance across for case5 (Figure 126).

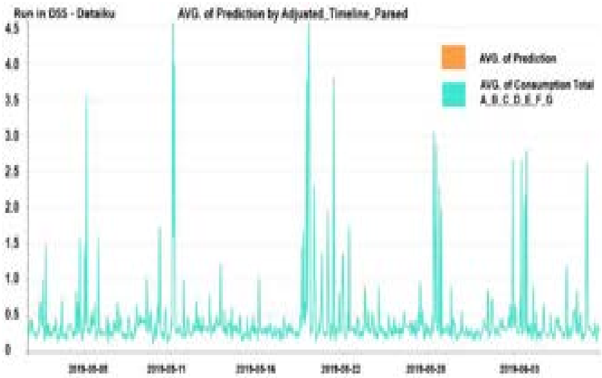


Figure 123: Case5_ 6-month consumption profile with lag function, using XGBoost algorithm

Figure 123 shows the prediction results (Case 5) using the XGBoost algorithm with lag function. Period: 01 May to 31 Oct 2018. The model returned 13% within the range of 0-5% and 11% for 5-10%. Many attempts have been tried; however, the model did not perform satisfactorily. (Figure 126

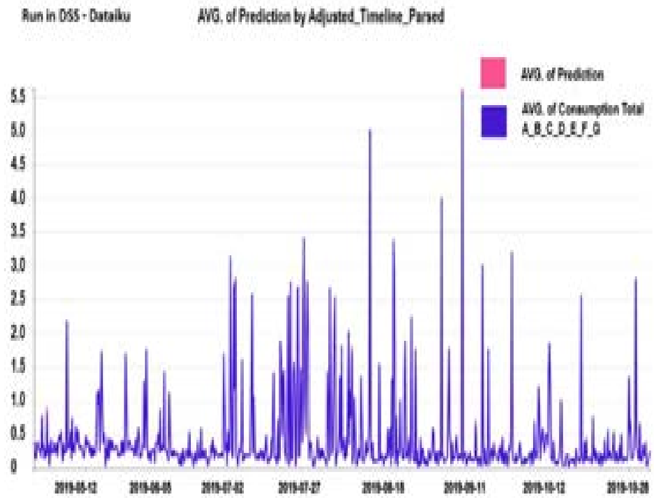


Figure 124: Case5_ 6-month consumption profile with lag function, using Random Forest algorithm

Figure 124 shows the prediction results using the Random Forest algorithm with lag function. The model returned 19% within the range of 0-5% and 17% for 5-10% (Figure 126). Many attempts have been tried; however, the model did not perform satisfactorily.

Figure 125 shows the snapshot from the DSS tool for case 5-Session, using Mean Average Error (MAE). The algorithms are represented in figure 29. Lasso Regression performed slightly better than XGBboost and Random Forest in this case, but the difference was negligible.

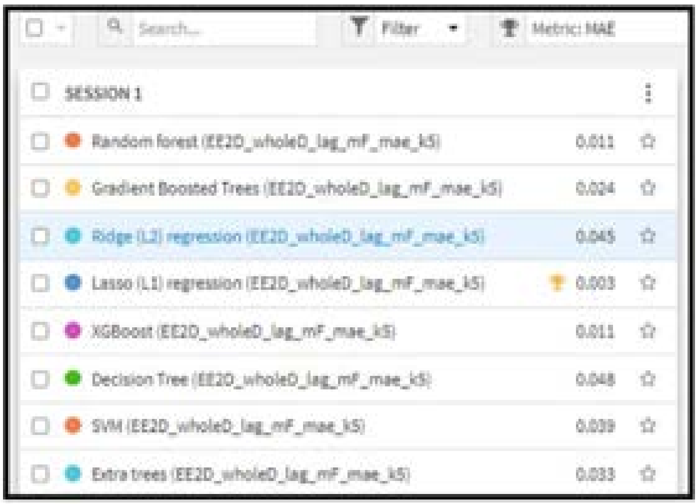


Figure 125: Case 5_model training results

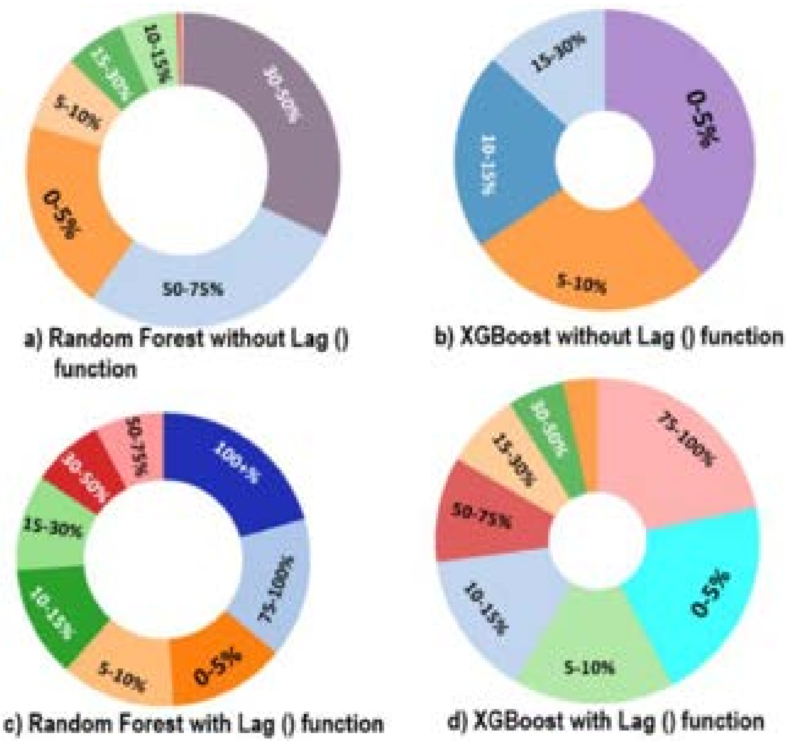


Figure 126: Case 5, metrics comparison

Figure 126 shows the bin error metrics results (Absolute Error Percentage Error - APE) for the four scenarios in Case 5 (1-minute interval). It compares lag vs no lag and Random Forest versus XGBoost algorithms. Charts a) and b) refer to the models trained without lag, and charts c) and d) refer to the models trained with lag. For charts a) and c) Random Forest was used, while Charts b) and d) XGBoost were used

6.4.6 CASE 6: PICOGRID MODELLING –@ 1-SECOND

Figure 127 shows the prediction results (Case 6) using XGBoost without lag function. Period: 01 May to 31 Oct 2018. The model returned 28% within the range of 0-5% and 11% for 5-10% (Figure 132). Many attempts have been tried; however, this model did not perform satisfactorily.

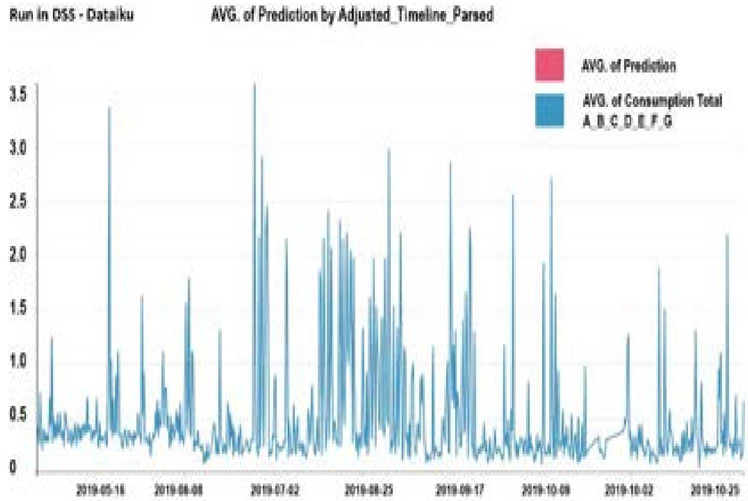


Figure 127: Case 6, 6-month consumption, without lag function, using XGBoost algorithm

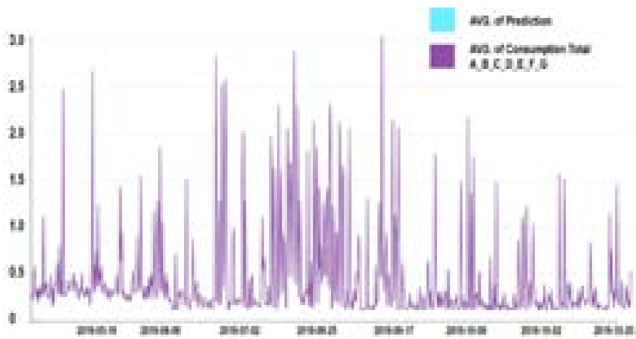


Figure 128: Case 6, 6-month consumption profile without lag function, using Random Forest algorithm

Figure128 shows the model prediction results using the Random Forest algorithm without the sliding window function. The model returned 20% within the range of 0-5% and 12% for 5-10% (Figure 132). Many attempts have been tried, but the model did not perform as expected.

Figure 129 shows the model prediction using the XGBoost algorithm with lag function. The model returned 23% within the range of 0-5% and 7% for 5-10% (Figure 132). Many attempts have been tried; however, the model did not perform satisfactorily.

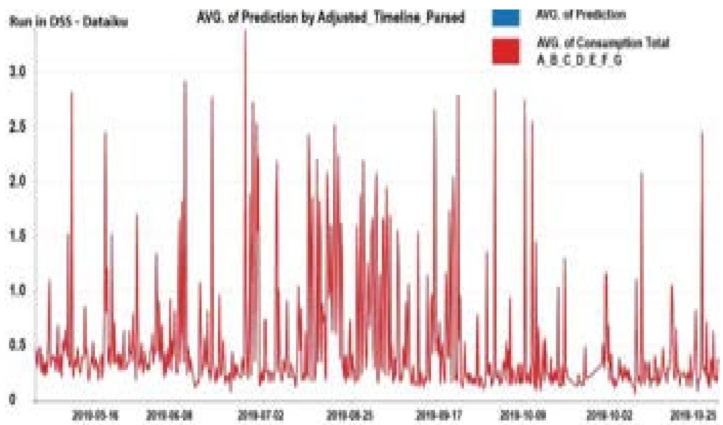


Figure 129: Case 6_6 month consumption profile with lag function, using XGBoost algorithm

Figure 130 shows the prediction results using Random Forest algorithm with lag function. The model returned 10% within the range of 0-5% and 3% for 5-10% (Figure 132). Many attempts have been tried; however, the model did not perform satisfactorily.

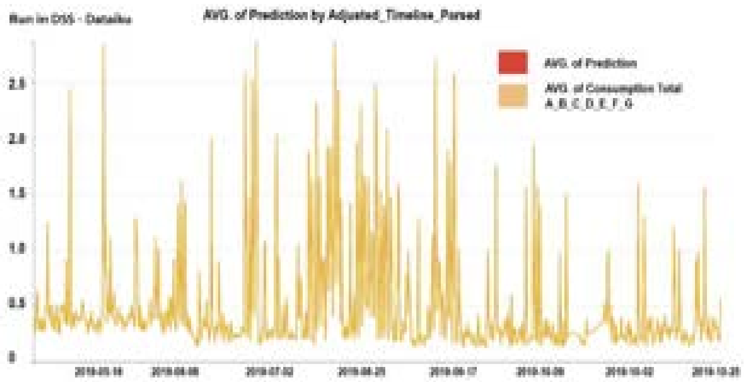
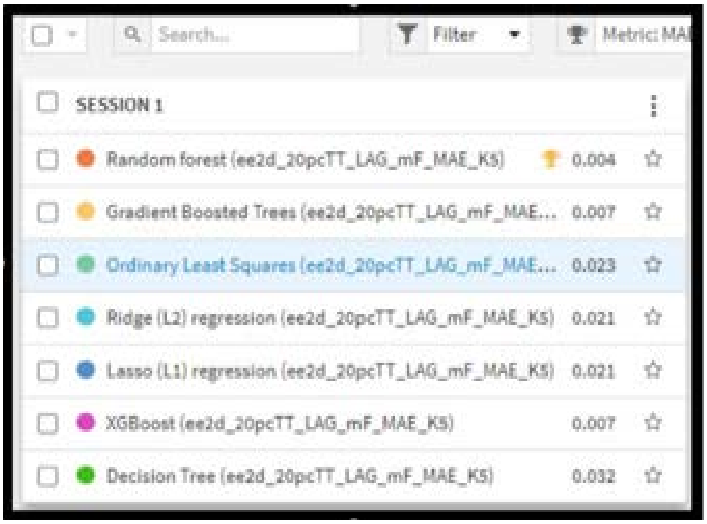


Figure 130: Case 6, 6-month consumption profile with lag function, using Random Forest algorithm



SESSION 1		
Random forest (ee2d_20pcTT_LAG_mF_MAE_KS)	0.004	
Gradient Boosted Trees (ee2d_20pcTT_LAG_mF_MAE...	0.007	
Ordinary Least Squares (ee2d_20pcTT_LAG_mF_MAE...	0.023	
Ridge (L2) regression (ee2d_20pcTT_LAG_mF_MAE_KS)	0.021	
Lasso (L1) regression (ee2d_20pcTT_LAG_mF_MAE_KS)	0.021	
XGBoost (ee2d_20pcTT_LAG_mF_MAE_KS)	0.007	
Decision Tree (ee2d_20pcTT_LAG_mF_MAE_KS)	0.032	

Figure 131: Case 6_model training results

Figure 131 shows the snapshot from the DSS tool for case 6 Session1, using Mean Average Error (MAE). Random Forest performed slightly better than XGBboost, although the difference was negligible.

Figure 132 shows the bin errors (the percentiles for Absolute Error Percentage Error - APE) for the four scenarios in Case 6 (l-second interval). It compares lag vs no lag and Random Forest versus XGBoost algorithms. Charts a) and b) refer to the models trained without lag, and charts c) and d) refer to the models trained with lag. For charts a) and c) Random Forest was used, while Charts b) and d) XGBoost were used.

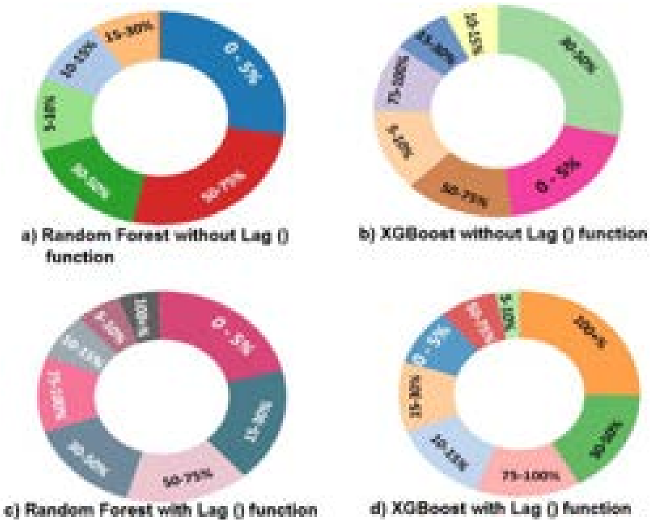


Figure 132: Case 6 metrics comparison

6.5 DISCUSSING THE MODELLING RESULTS AND INSIGHTS

							Results Summary				
		Period of Collection	Number of rows	Splitting rates modelling		Nr rows	Error Range	XGBoost	Random Forest	NoLag	LAG
Case_1	Microgrid_ 15Min	365 days	2,120,402	Training	78%	1,653,914	0-5%	71.5%	67.2%	62.5%	76.2%
				Validation	18%	381,673	0-10%	87.9%	83.3%	80.7%	90.6%
				Test	4%	84,817					
Case_2	Nanogrid_ 15Min	365 days	873,279	Training	78%	681,158	0-5%	76.4%	62.9%	68.5%	70.8%
				Validation	18.00%	157,191	0-10%	91.8%	79.8%	85.1%	86.6%
				Test	4.00%	34,932					
Case_3	Nanogrid_ 1Min	365 days	13,100,558	Training	78%	10,218,436	0-5%	67.3%	71.5%	64.6%	74.2%
				Validation	18%	2,358,101	0-10%	80.7%	83.1%	78.1%	85.7%
				Test	4%	524,023					
Case_4	Picogrid_ 15Min	183 days	17,664	Training	78%	13,778	0-5%	26.4%	25.1%	25.7%	25.8%
				Validation	18%	3,180	0-10%	45.9%	44.1%	45.4%	45.6%
				Test	4%	707					
Case_5	Picogrid_ 1Min	183 days	264,960	Training	78%	206,669	0-5%	90.4%	82.4%	83.5%	87.6%
				Validation	18%	47,693	0-10%	97.3%	94.4%	94.3%	97.5%
				Test	4%	10,599					
Case_6	Picogrid_ 1Sec	183 days	15,897,668	Training	78%	12,400,182	0-5%	89.0%	87.6%	84.9%	91.7%
				Validation	18%	2,861,581	0-10%	97.9%	98.2%	97.7%	98.5%
				Test	4%	635,907					

Table 11: *Case study comparison based on error ranges*

Table 11 provides an overview of the six cases covered in this study. The results prove that power consumption prediction is attainable for *picogrids*, *nanogrids* and *microgrids*, given that data is available for at least six months with frequency of 1-second for picogrids and at least 1 year for both nanogrids and microgrids with frequencies of 1 minute and 15 minutes, respectively.

The performance analysis shows that XGBoost and Random Forest perform better than the other investigated models with a performance accuracy of 98% within the 0-10% absolute percentile error (APE) range.

Automated predictions can enable automatic analytics, leading to customised user feedback. It helps the *microgrid* and *nanogrid* systems to learn the consumption profile for a householder or group of users, so continuous planning improvements can be incrementally added.

The prediction accuracy and computational cost tradeoffs must be factored in to meet individual needs. A highly accurate system demands a huge amount of real-time data, which may take days of computation until results are produced. Conversely, a fast system with low precision may not yield the desired outcome for problem mitigation. Since there are many machine learning algorithms for prediction, classification and decision-making, this study mostly focuses on XGBoost and Random Forest.

Predicting electricity consumption and power supply is vital for small-scale autonomous DC power plants. A detailed consumption profile per use category enables prioritising tasks and educating the user to act preventively to avoid power shortages. A greater understanding of the demand per use category is essential for mitigating power requirements. The BAIoTAG framework enables several subsystems to interact so automated decisions can be implemented, and of these patterns, the greater the chances to improve service quality.

AI agents can learn consumption profiles for a group of users, so continuous improvements can be incrementally added. The prediction accuracy and computational cost tradeoffs must be factored in on a case-by-case basis. A highly accurate system may demand a huge amount of real-time data, which may take days of computation until results are produced. Conversely, a fast system with low precision may not yield the desired outcome for problem mitigation.

Conversely, a fast system with low precision may not yield the desired outcome for problem mitigation. Since there are many machine learning algorithms for prediction, classification and decision-making, this study mostly focuses on XGBoost and Random Forest. The results prove that power consumption prediction is attainable for *picogrids*, *nanogrids* and *microgrids*, given that data is available for at least six months and frequency of 1-second for picogrids, 1 minute for *nanogrid* and 15 minutes for *microgrids*. The performance analysis shows that XGBoost and Random Forest perform better than the other investigated models with a performance accuracy of 98% within the 0-10% absolute percentile error (APE) range.

Chapter 7: Conclusion and Future Work

Humanity has become locked in on fossil fuels for survival – and nothing is wrong with that, except for GHG emissions. The dependency on natural resources is a fact that cannot be changed. Irresponsible consumption and reckless transformation methods leading to producing goods, objects, and all the infrastructure can and must be changed. However, changing consumer behaviour is difficult since the largest corporations work in the very opposite direction. Also, changing the transformation methods is problematic since the state establishes the ground rules on who, how and what to be done. Moreover, the world has become vastly dominated by specialists who care very little about consumer behaviour and transformation methods and their effects on the planet. The curse of specialisation makes people narrowly focused - since they cannot see the big picture, misinformation becomes widespread.

This thesis has shown that reducing global GHG emissions from the electricity industry is possible by deploying a comprehensive framework accounting for all the root causes combined. Without understanding the whole context, the economics, the importance of raising public awareness, and the need to have an alternative path, there is little hope for positive changes. In Chapter 4, this thesis investigated in depth the causes, sources, drivers and root causes of the global emissions. It shows why all the existing strategies have failed to address climate change, the conflict of interests, and the millions of organisations that benefit from emissions. After determining the root causes and exposing the complexities and dependencies, it was possible to devise a path to the future. In Chapter 5, this thesis presented the ADCx model, the BAIoT system and the BAIoTAG framework.

Whereas Chapter 4 clarified the problem, Chapter 5 focused on the solution. It is impractical to foresee a solution to compete with the existing power grid since it has been built on legislation that encourages emissions and undermines any form of competition. Thus, Chapter 5 introduces the ADCx model, away from the existing grid, a bottom-up approach spearheaded by users. A parallel infrastructure must exist capable of providing options to adopt a low-carbon lifestyle. Whereas ADCx focuses on the infrastructure, the BAIoT system brings intelligence, analytics and trusted communications rail enabled by Blockchain, AI, and IoT. The BAIOTAG framework was conceived to enable tools, incentives, and advantages can be introduced to support users to make better choices. Many of the new advantages cannot be achievable by the existing grid.

In chapter 6, a comparative case study was presented to prove that power consumption prediction is attainable for *picogrids*, *nanogrids* and *microgrids*, given that data is available for at least six months and frequency of 1-second for *picogrids*, 1 minute for *nanogrid* and 15 minutes for *microgrids*. Prediction is vital for small-scale and autonomous DC power plants since optimises resources to compensate for stochastic problems in power generation. When a system only focuses on short-term benefits, scalability and profitability are coupled, and pollution is the natural outcome. Conversely, in small-scale power plants, a long-term view is paramount. The performance analysis shows that XGBoost and Random Forest perform better than the other investigated models with a performance accuracy of 98% within the 0-10% absolute percentile error (APE) range.

7.1 MAIN CONTRIBUTIONS AND FINDINGS

Major contributions and research outcomes include:

(1) Creating a unique approach for deciphering the global emissions problem – by separating causes, sources, drivers, and root causes. Supports the education of researchers and the public on global emissions' ramifications and complexities.

(2) Untangling the differences between emission freeloaders, emission producers, and passive beneficiaries - shedding light on the gap between territorial and global emissions versus global sustainability (and net-zero);

(3) Formulates that the emissions problem is a global-common management dilemma that cannot be solved individually by each nation-state – without coordination, cooperation, and trust. Establishes the pressing need for a form of global management authority to establish accountability for mitigation and overcome state sovereignty.

(4) Features the seven root causes of global emissions in a unique diagram, providing specific context and insights for each root cause.

(5) Presents the ADCx model, an alternative solution to the electricity industry based on small and autonomous DC power plants, totally isolated from the AC power grid; It promotes freedom for a system that pollutes and depletes the planet; Introduces a hierarchical design model including autonomous *picogrids*, *nanogrids* and *microgrids*. The ADCx induces the creation of small power cooperatives where neighbours can share resources and knowledge;

(6) Launches the concept of *femtogrids*, which is unique in the academic literature; by learning specifics on how households use electricity for each use category (e.g., cooking, entertainment, comfort), it is possible to determine accurate patterns and consumer behaviour; which enables the introduction of AI and ML algorithms to support users on making better choices, prioritise tasks, saving energy and more.

(7) Presented the BAIoT system, which enables the transfer of accountability from the state to the community and household level; BAIoT stimulates rational consumption, helping to educate users to find the middle point between needs and desires;

(8) Clarifying that it is the user who triggers the global emissions flow, not the producers; so, reducing global emissions requires enabling tools, techniques, and infrastructure so users can educate themselves, change behaviours, and make consistent pro-environmental choices.

(9) Showing that instead of using technology to stimulate more sales and acquisitions (like vendors, media, and advertisers), it can be used in the opposite direction to shield consumers against unbounded purchases and consumption;

(10) Demonstrating that Blockchain, AI, and IoT can work together to support and guide users towards their sustainability journey; BAIoT creates a pathway for users to take accountability for their direct and indirect emissions (e.g., embedded on goods and objects or embodied on buildings);

(11) Illuminating that only a global solution accounting for all the root causes together can solve the global emission problem; partial solutions, such as the "transition to renewables" or "ultra-large battery coupled with solar power", will not substitute the need for fossil fuels – as they only help the emission problem getting worse.

(12) Shedding light on the importance of artificial intelligence and analytics to support users to reach sustainability and avoid the rebound effect;

(13) Highlighting the BAIoT capabilities in supporting Local economy development (LED) and *circular economy.* Enabling the exchange of private and sensitive data among users (which would be unattainable for the existing system (AC power grid); provides a new pathway for the cluster of consumers willing to act to reduce their emissions and make their contribution to tackling the emissions problem without relying on governmental actions.

(14) Trigger the decision-makers to create more efficient laws for protecting the environment.

(15) Enables individuals, organisations, and communities to become self-organised, take accountability for emissions, and solve their energy requirements locally; create

stronger collaboration within a neighbourhood, facilitating the exchange of experiences, discoveries, and learned lessons and encouraging new approaches.

(16) Encourages more local businesses, electrical cooperatives, local and small-scale service providers, and local jobs for microgrid and nanogrid network operators.

(17) Enable householders to measure their carbon footprint, take corrective actions, and get their properties certified as eco-sustainable (e.g., net-zero emission for 12 months).

(18) Improve consumer habits - by discouraging time-wasting activities (e.g., excessive social media) and encouraging healthier activities.

(19) Highlights the importance of using technology to motivate healthier competition among neighbourhoods to improve their sustainability; reduce energy waste and save electricity by avoiding appliances that bring no added value to the user; enabling resource sharing, and helping to improve system reliability and availability.

(20) Trigger vendors to produce D.C. appliances, avoiding unnecessary conversions and power waste.

(21) IoT-Blockchain enables peer-to-peer data sharing between machines without losing privacy (the opposite of data aggregators).

(22) BAIoTAG is replicable, capable of crossing borders and being deployed anywhere.

7.2 FUTURE RESEARCH DIRECTIONS

The ADCx design model, BAIoT system, and the BAIoTAG framework require specific system development tools to integrate the many sub-components, allowing automation and customised user feedback. Research performed for this thesis may be extended as follows:

i) Blockchain can help in shifting how communities and householders deal with energy trading. It can serve as a communication and payment rail, supporting Local Economic Development and Circular Economy. Blockchain enables the development of strategies to implement motivational factors within consensus protocol and demonstrate how it can work in real life. Future research should include the implementation of a hybrid Blockchain for the communication between *microgrids*, *nanogrids* and *picogrids*.

ii) Devising new methods for tracking emissions associated with the products and services. Most products have components produced abroad, where no data are available. There must be reliable methods to establish emission forensics and provenance, and accountability.

iii) Re-designing processes to leverage emissions from coal, gas, and oil. There are many approaches how to mitigating emissions near the sources. Solving a small-scale and local problem differs greatly from large-scale and global problems.

iv) measurement tool to assess eco-sustainability covering aquatic, terrestrial and atmospheric ecosystems. (Not as simplistic as typical LCAs approaches, nor as complex as EIAs (Environmental Impact Assessment)

v) Create a peer-to-peer energy exchange module linked to a Blockchain platform (e.g., Hyperledger Fabric) with *smart contract* functionalities, enabling bartering, trading or sharing. User interfaces for visualisation and monitoring must exist, allowing householders access to their own private data.

vi) IoT Agents must be capable of automatically collecting consumption data (via sensors), creating CSV files, and publishing results in the Blockchain. Conversely, AI agents will access and act on the data to make predictions and recommendations. Results must be published on the Blockchain so other authorised agents can access and action on it.

vii) Build a real case where a *nanogrid* is fully sustainable and viable. Integrate the modules of Blockchain, IoT and ML in a single package and test the end-to-end solution. Integrate the Load Management System with each house appliance.

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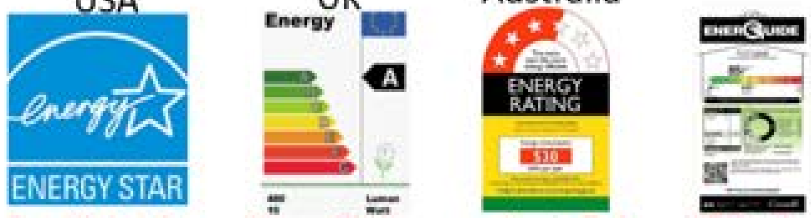
Appendices

Strategies to Motivate Low Carbon Lifestyle

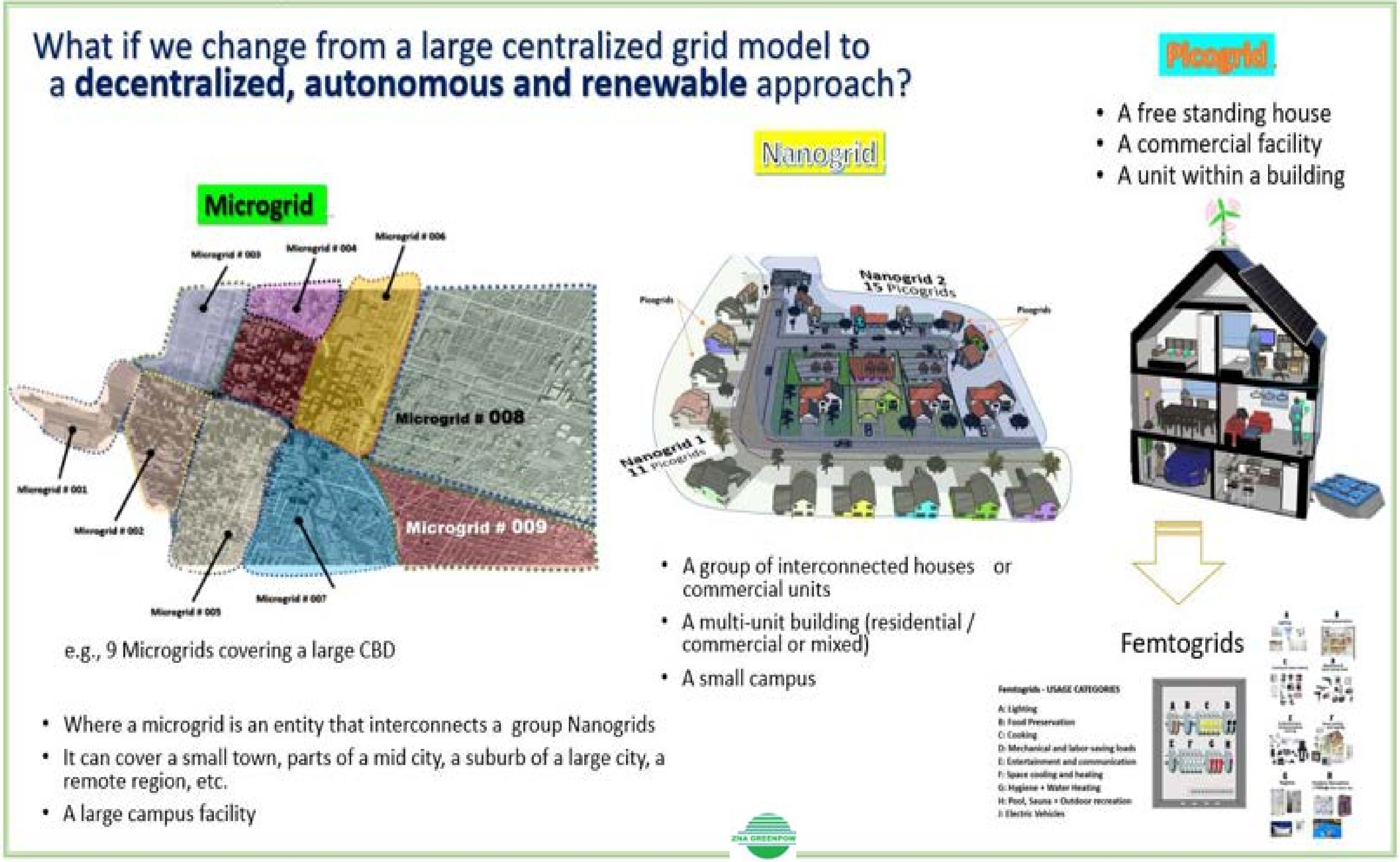
- **Rewarding scheme for users on the path towards carbon neutrality** (financial and appreciation rewards, star scheme for achievement & recognition, etc)
- **Delayed gratification –** get rewards later rather than now
- **Use of technology to gradually raise user awareness towards sustainability without overwhelming with many technical details**
- **Rating scheme for achievement & recognition** (houses with lower per-capita consumption, higher sustainability indicators, higher market price)
- **Sustainability indicators for the Picogrids, Nanogrids and Microgrids**
- **Enable innovative competition practises among stakeholders towards decarbonization and sustainability**
  E.g. enables power auction among cities, regions, states, countries, which leads to a healthy competition environment

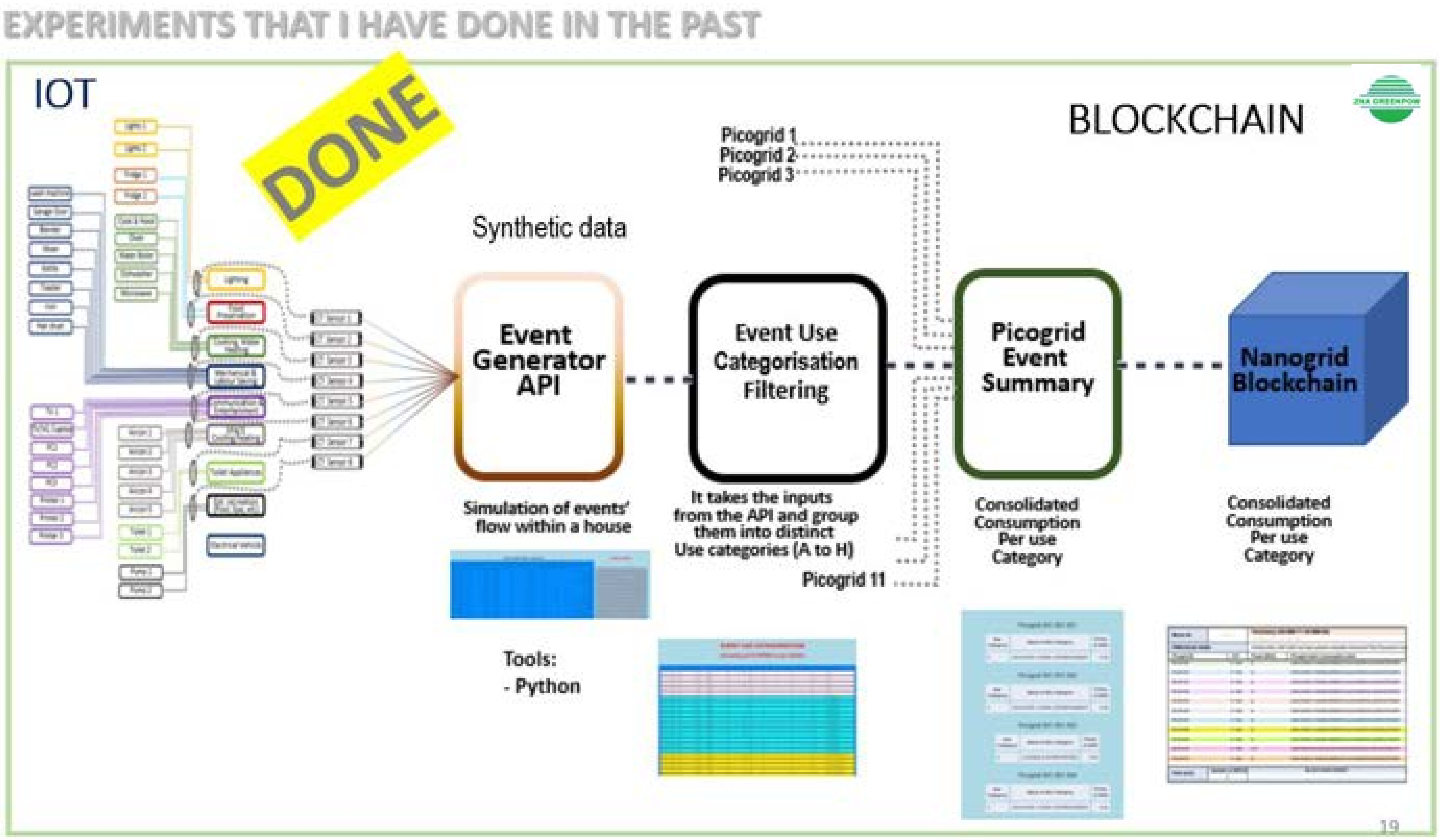
USA UK Australia Canada

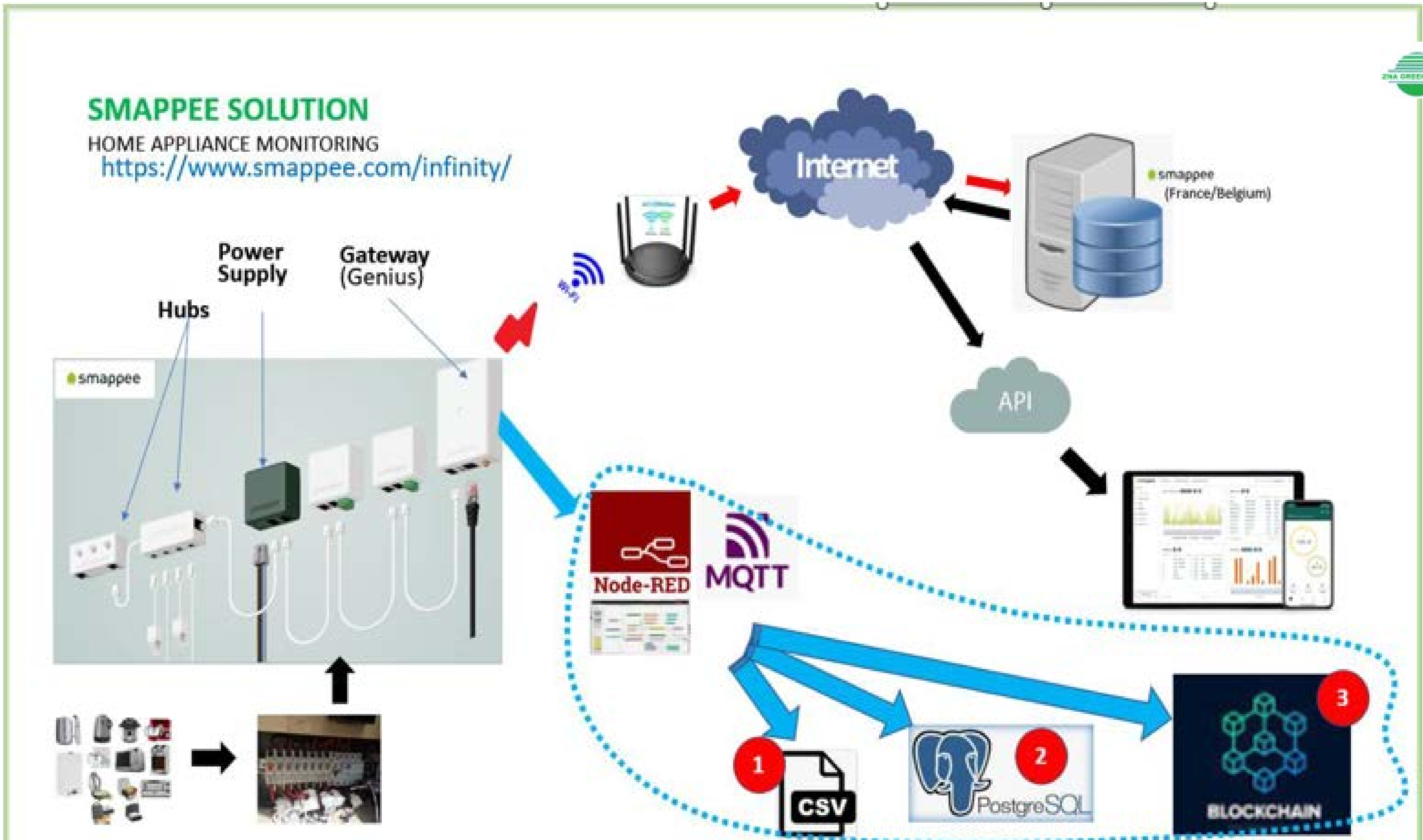


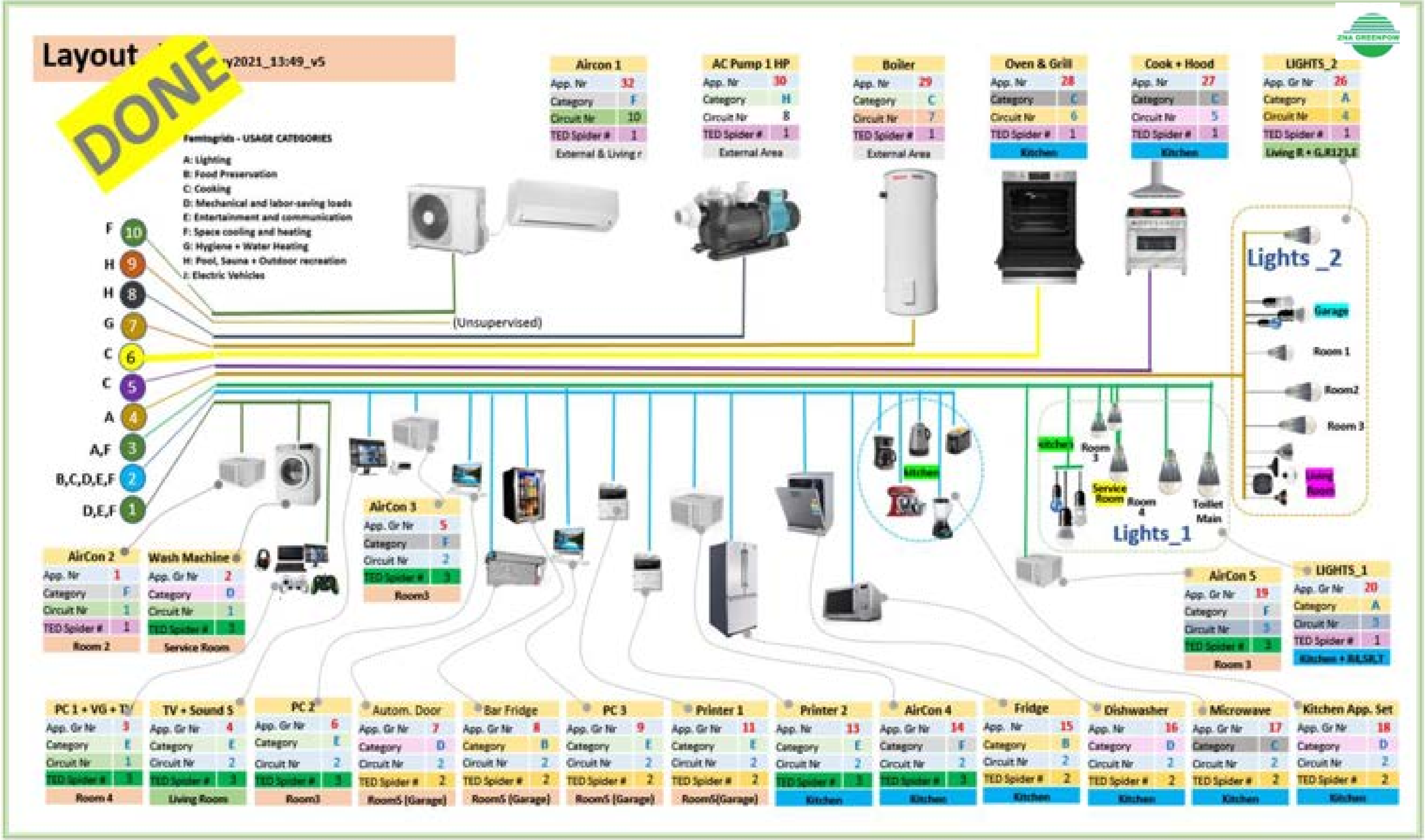
Good intension and low effectiveness due to Rebound Effect!

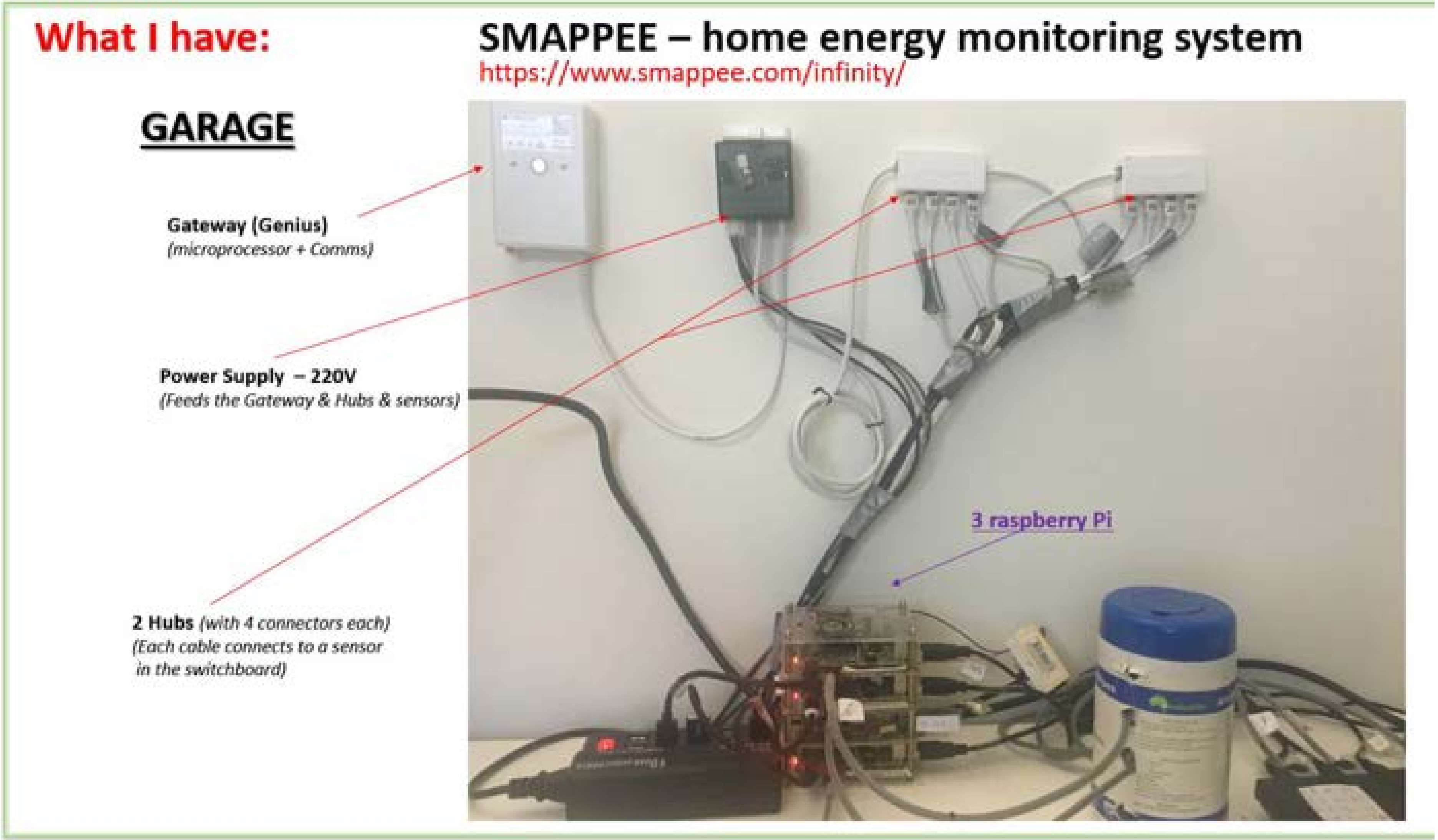
15


What if we change from a large centralized grid model to
a **decentralized, autonomous and renewable** approach?
Microgrid
Microgrid # 008
Microgrid # 009
e.g., 9 Microgrids covering a large CBD
• Where a microgrid is an entity that interconnects a group Nanogrids
• It can cover a small town, parts of a mid city, a suburb of a large city, a remote region, etc.
• A large campus facility
Nanogrid
Nanogrid 2
15 Picogrids
Nanogrid 1
11 Picogrids
• A group of interconnected houses or commercial units
• A multi-unit building (residential / commercial or mixed)
• A small campus
Picogrid
• A free standing house
• A commercial facility
• A unit within a building
Femtogrids

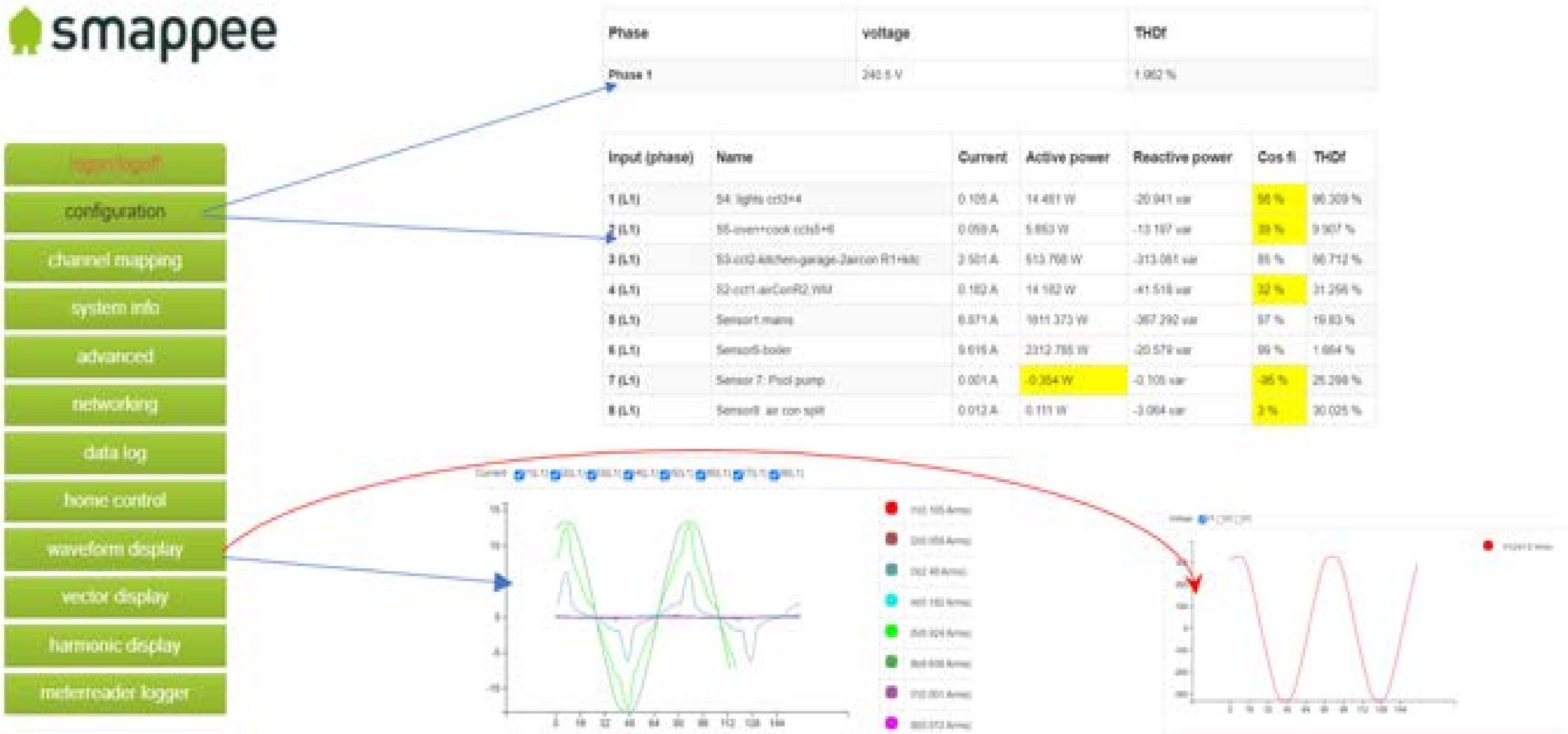

EXPERIMENTS THAT I HAVE DONE IN THE PAST
IOT
DONE
BLOCKCHAIN
Synthetic data
Picogrid 1
Picogrid 2
Picogrid 3
Event Generator API
Event Use Categorisation Filtering
Picogrid Event Summary
Nanogrid Blockchain
Simulation of events' flow within a house
It takes the inputs from the API and group them into distinct Use categories (A to H)
Picogrid 11
Consolidated Consumption Per use Category
Consolidated Consumption Per use Category
Tools:
- Python
19


SMAPPEE SOLUTION
HOME APPLIANCE MONITORING
https://www.smappee.com/infinity/
Power Supply
Gateway (Genius)
Hubs
smappee
Internet
smappee
(France/Belgium)
API
Node-RED
MQTT
1
CSV
2
PostgreSQL
3
BLOCKCHAIN


Layout
DONE
Femtogrids - USAGE CATEGORIES
A: Lighting
B: Food Preservation
C: Cooking
D: Mechanical and labor-saving loads
E: Entertainment and communication
F: Space cooling and heating
G: Hygiene + Water Heating
H: Pool, Sauna + Outdoor recreation
I: Electric Vehicles
(Unsupervised)
Aircon 1
AC Pump 1 HP
Boiler
Oven & Grill
Cook + Hood
LIGHTS_2
Lights _2
Lights_1
AirCon 2
Wash Machine
AirCon 3
AirCon 5
LIGHTS_1
PC 1 + VG + TV
TV + Sound S
PC 2
Autom. Door
Bar Fridge
PC 3
Printer 1
Printer 2
AirCon 4
Fridge
Dishwasher
Microwave
Kitchen App. Set

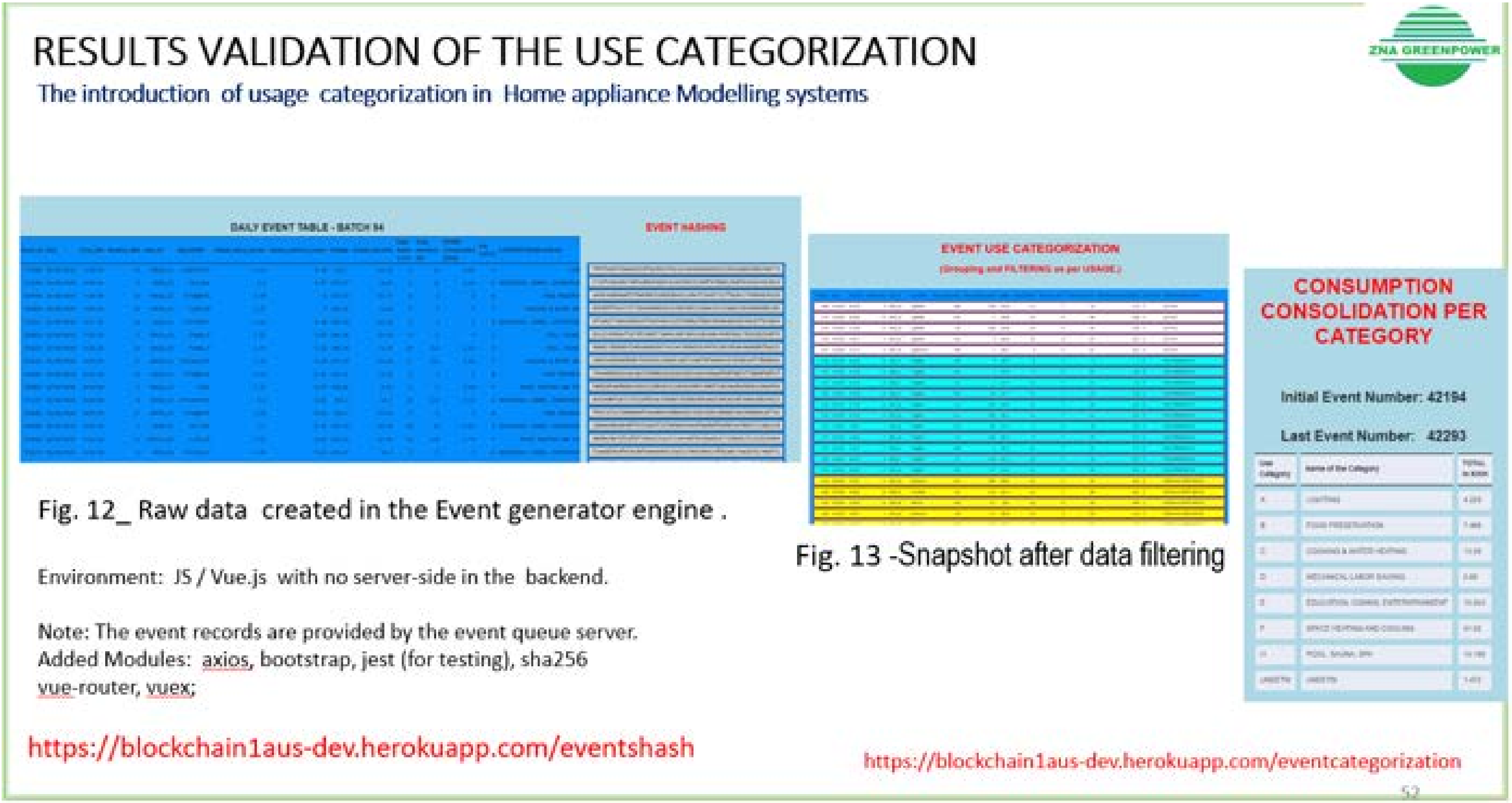

What I have:
SMAPPEE – home energy monitoring system
https://www.smappee.com/infinity/
GARAGE
Gateway (Genius)
(microprocessor + Comms)
Power Supply – 220V
(Feeds the Gateway & Hubs & sensors)
2 Hubs (with 4 connectors each)
(Each cable connects to a sensor
in the switchboard)
3 raspberry Pi

- ❖ The Smappee microprocessor (Genius Gateway) is connected to my local Wi-Fi on IP 192.168.1.102
- ❖ When I log onto the Genius dashboard, http://192.168.1.102/smappee.html I can see the following info:



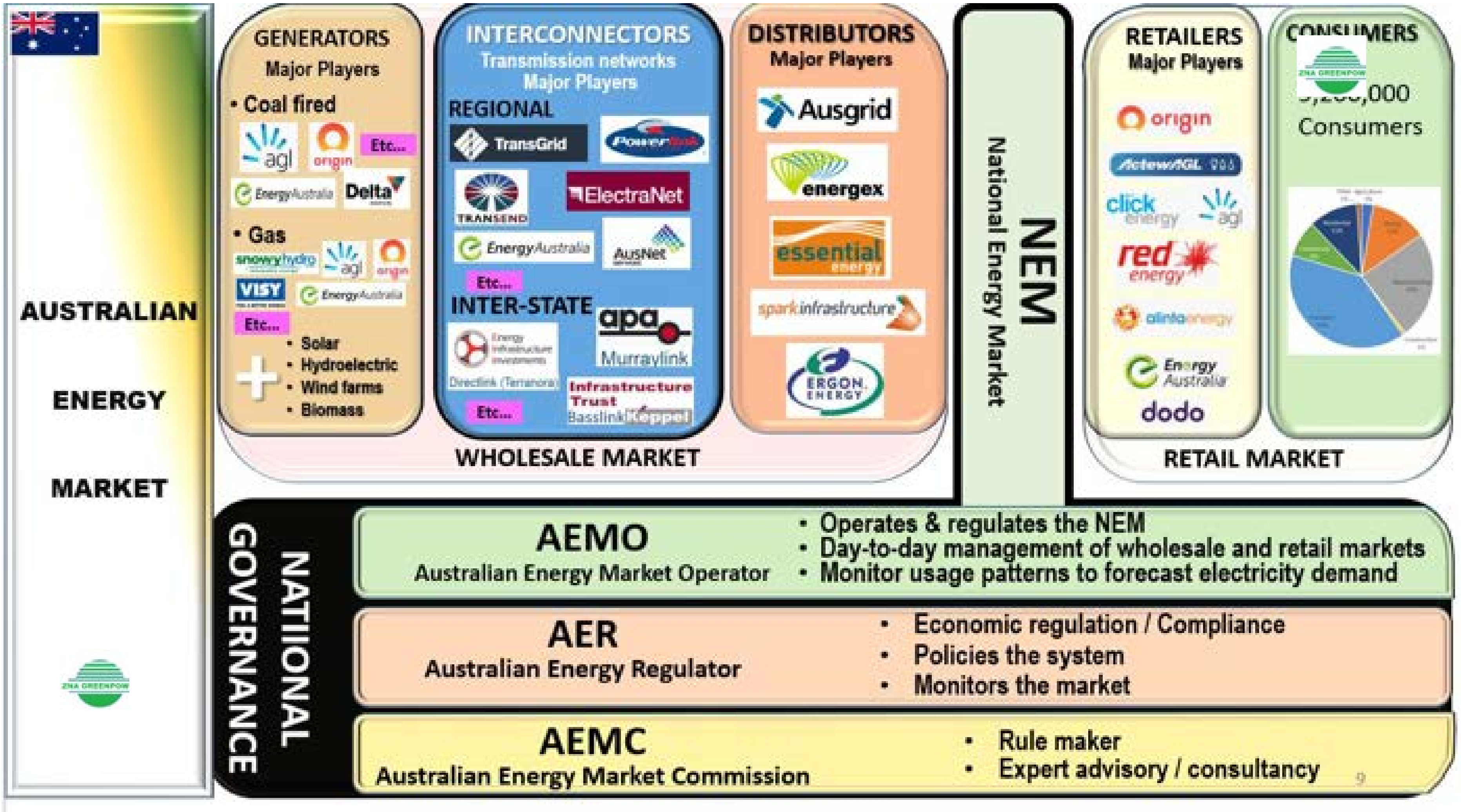
Phase	voltage	THDf
Phase 1	240.5 V	1.962 %

Input (phase)	Name	Current	Active power	Reactive power	Cos fi	THDf
1 (L1)	54: lights cct3+4	0.105 A	14.451 W	-20.941 var	56 %	96.309 %
2 (L1)	55-oven+cook cct5+6	0.059 A	5.853 W	-13.197 var	39 %	9.907 %
3 (L1)	53-cct2-kitchen-garage-2aircon R1+k&	2.501 A	513.708 W	-313.081 var	85 %	56.712 %
4 (L1)	52-cct1-airConR2.WM	0.182 A	14.182 W	-41.518 var	32 %	31.256 %
5 (L1)	Sensor1 mains	6.871 A	1611.373 W	-367.292 var	97 %	19.83 %
6 (L1)	Sensor6-boiler	9.616 A	2312.785 W	-20.579 var	99 %	1.664 %
7 (L1)	Sensor 7: Pool pump	0.001 A	-0.354 W	-0.105 var	-95 %	25.298 %
8 (L1)	Sensor8: air con split	0.012 A	0.111 W	-3.064 var	3 %	30.025 %

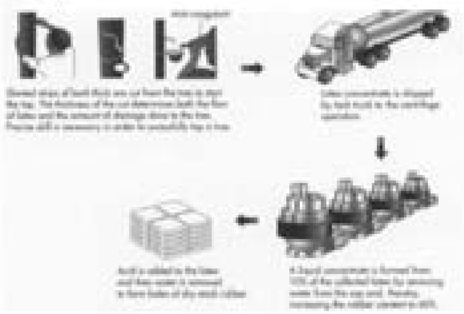

RESULTS VALIDATION OF THE USE CATEGORIZATION
The introduction of usage categorization in Home appliance Modelling systems
ZNA GREENPOWER
DAILY EVENT TABLE - BATCH 94
EVENT HASHING
EVENT USE CATEGORIZATION
(Grouping and FILTERING as per USAGE)
CONSUMPTION CONSOLIDATION PER CATEGORY
Initial Event Number: 42194
Last Event Number: 42293
Fig. 12_ Raw data created in the Event generator engine .
Fig. 13 -Snapshot after data filtering
Environment: JS / Vue.js with no server-side in the backend.
Note: The event records are provided by the event queue server.
Added Modules: axios, bootstrap, jest (for testing), sha256
vue-router, vuex;
https://blockchain1aus-dev.herokuapp.com/eventshash
https://blockchain1aus-dev.herokuapp.com/eventcategorization
52

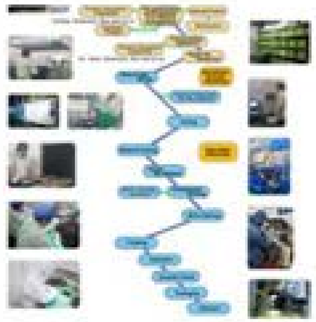
Sample data from a Nanogrid Service Provider_Output2_Data Summary for ledger2_peer_to_peer recordings

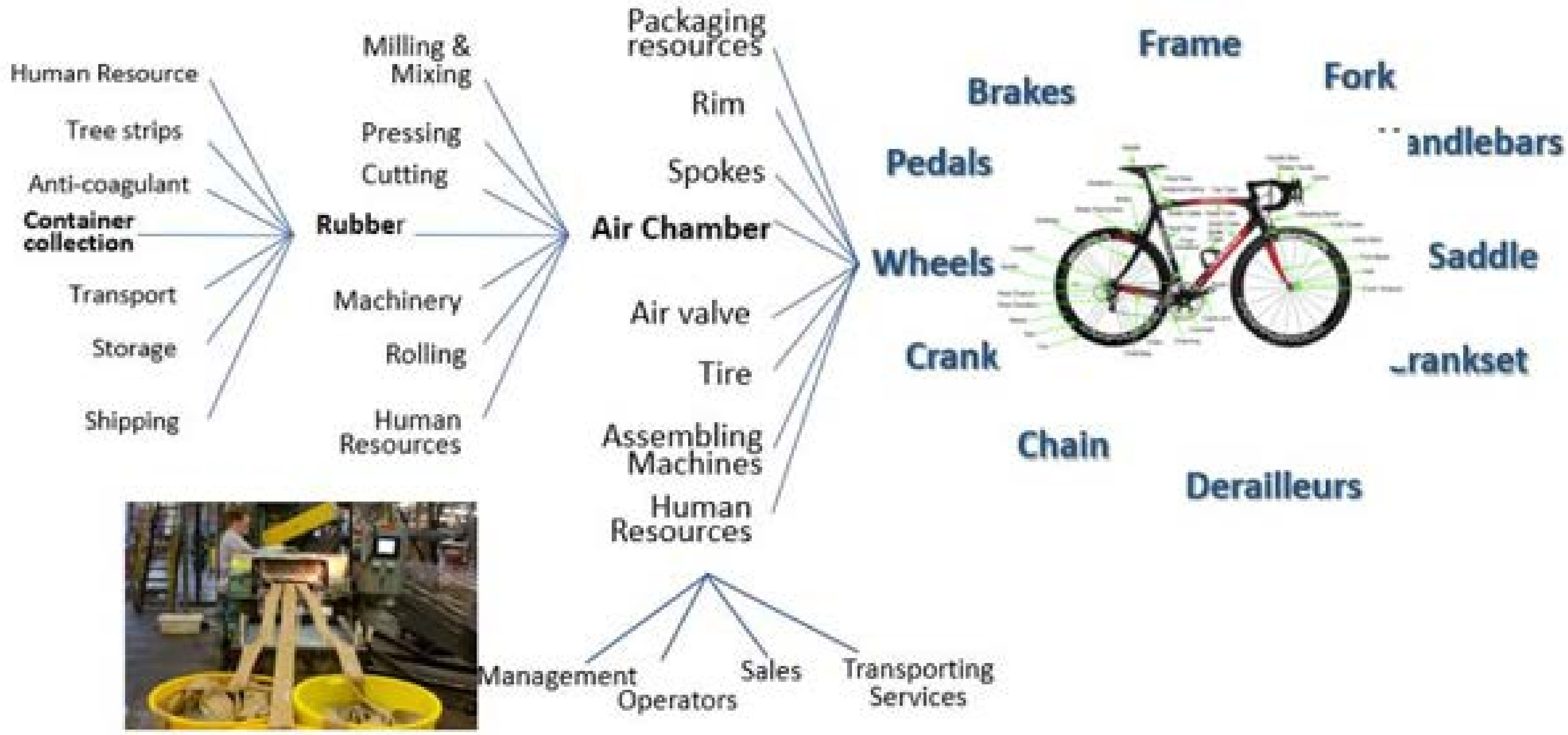
	A	B	C	D	E	F	G	H	I	J	K
1	House_ID	Timestamp	Power_CONSUMPTION_total_W	Power_GENERATED_W	Power_GENERATION_capacity_W	Power_STORED_total_KVH	Power_STORAGE_capacity_KVH	Energy_EXPORTED_total_W	Energy_EXPORTED_to_WHOM_houseID	Energy_IMPORTED_total_W	Energy_IMPORTED_from_WHOM_houseID
2	3008	1/01/2021 0:00	5.589	9.974	10.0	0.288	4	0.148	3011	0	3005
3	3002	1/01/2021 0:00	0.452	2.157	6.0	5.954	9	0.029	3009	0	3010
4	3009	1/01/2021 0:00	5.090	1.168	6.0	1.135	5	0.74	3003	0	3007
5	3005	1/01/2021 0:00	4.893	4.551	5.0	3.732	7	0.744	3002	0	3002
6	3010	1/01/2021 0:00	2.948	5.406	5.0	5.977	9	0.798	3004	0	3010
7	3008	1/01/2021 0:00	2.819	1.584	6.0	0.046	4	0.922	3005	0	3003
8	3008	1/01/2021 0:00	5.418	5.983	7.0	1.672	5	0.203	3002	0	3006
9	3005	1/01/2021 0:00	5.762	5.804	2.5	0.788	4	0.417	3003	0	3001
10	3003	1/01/2021 0:00	5.498	4.888	10.0	2.673	6	0.338	3009	0	3005
11	3009	1/01/2021 0:00	2.484	5.41	5.0	2.98	6	0.455	3008	0	3009
12	3007	1/01/2021 0:01	4.478	1.021	2.5	0.716	4	0.29	3008	0	3001
13	3009	1/01/2021 0:01	3.147	2.803	10.0	2.759	6	0.935	3009	0	3006
14	3010	1/01/2021 0:01	4.320	5.628	7.5	1.93	5	0.949	3003	0	3009
15	3004	1/01/2021 0:01	2.914	4.48	6.0	4.291	8	0.182	3006	0	3004
16	3011	1/01/2021 0:01	4.677	2.494	7.5	1.639	5	0.989	3005	0	3006
17	3011	1/01/2021 0:01	3.247	1.758	5.0	1.841	5	0.93	3011	0	3011
18	3008	1/01/2021 0:01	0.452	0.305	2.5	2.913	6	0.997	3003	0	3002
19	3008	1/01/2021 0:01	1.736	2.7	7.6	4.749	8	0.511	3009	0	3003
20	3006	1/01/2021 0:01	4.146	3.193	10.0	0.473	4	0.127	3005	0	3011
21	3009	1/01/2021 0:01	4.098	3.251	8.8	5.925	9	0.43	3009	0	3003
22	3002	1/01/2021 0:01	3.212	2.896	5.0	0.802	4	0.941	3008	0	3011
23	3003	1/01/2021 0:02	5.443	1.554	3.5	3.549	7	0.896	3005	0	3008
24	3003	1/01/2021 0:02	1.183	1.637	7.5	3.309	7	0.737	3001	0	3008
25	3005	1/01/2021 0:02	5.099	4.241	4.0	0.277	4	0.362	3008	0	3011
26	3010	1/01/2021 0:02	0.043	5.312	5.0	5.039	9	0.699	3010	0	3007
27	3007	1/01/2021 0:02	1.705	4.616	5.0	5.139	9	0.152	3010	0	3009
28	3008	1/01/2021 0:02	1.226	5.791	6.0	2.451	6	0.618	3005	0	3004
29	3001	1/01/2021 0:02	5.145	2.717	3.0	5.529	9	0.016	3010	0	3001
30	3007	1/01/2021 0:02	4.813	2.979	3.0	0.969	4	0.419	3009	0	3001
31	3004	1/01/2021 0:02	4.237	3.298	3.0	5.0000	8	0.634	3002	0	3010
32	3002	1/01/2021 0:02	4.257	4.153	4.0	3.815	7	0.048	3006	0	3008

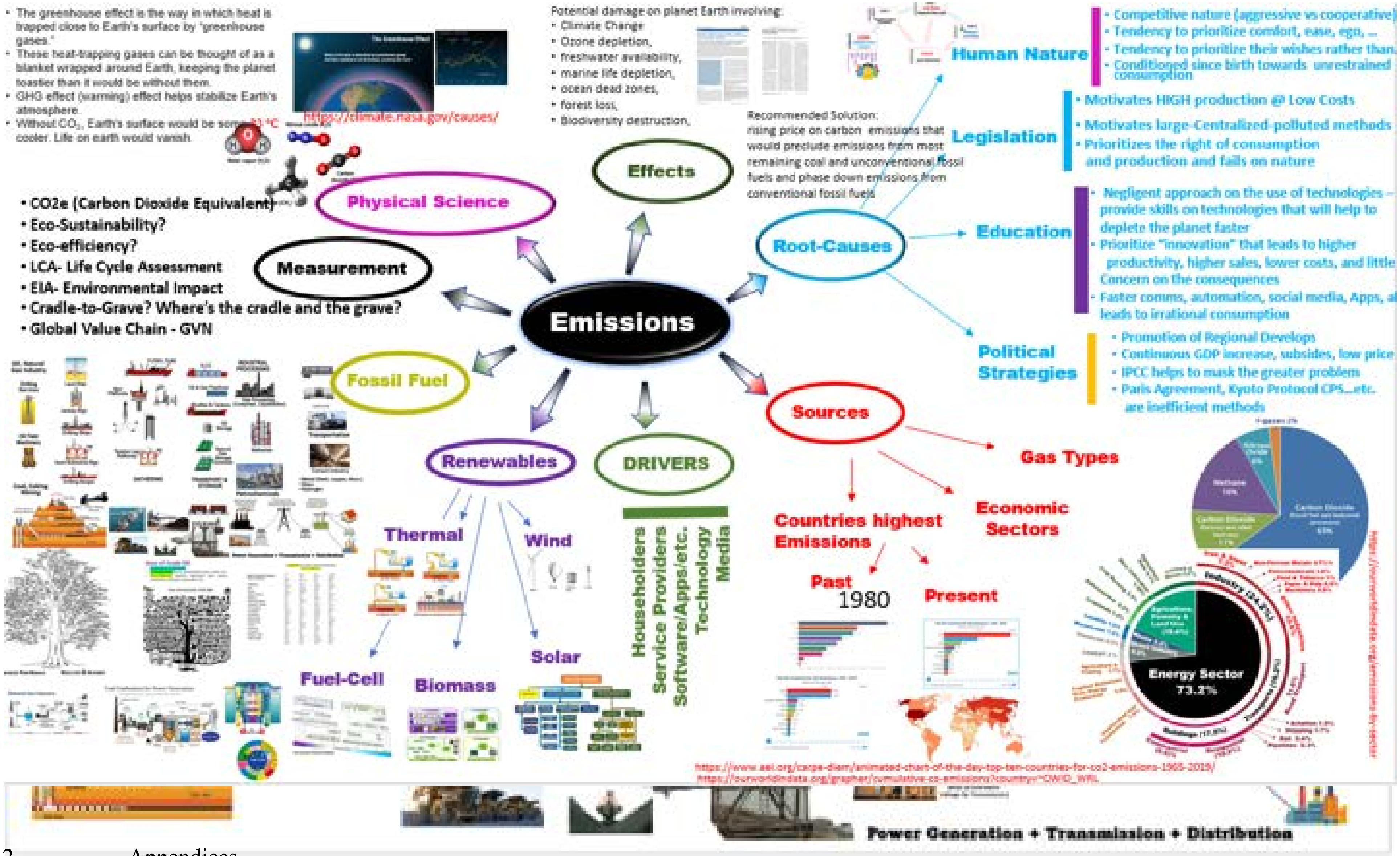

AUSTRALIAN
ENERGY
MARKET
GENERATORS
Major Players
• Coal fired
Etc...
• Gas
Etc...
• Solar
• Hydroelectric
• Wind farms
• Biomass
INTERCONNECTORS
Transmission networks
Major Players
REGIONAL
TransGrid
ElectraNet
Etc...
INTER-STATE
Murraylink
Directlink (Terranora)
Infrastructure Trust
Basslink
Etc...
DISTRIBUTORS
Major Players
Ausgrid
energex
essential energy
sparkinfrastructure
ERGON ENERGY
WHOLESALE MARKET
NEM
National Energy Market
RETAILERS
Major Players
origin
ActewAGL
click energy
agl
red energy
alinta energy
Energy Australia
dodo
CONSUMERS
Consumers
RETAIL MARKET
NATIONAL GOVERNANCE
AEMO
Australian Energy Market Operator
• Operates & regulates the NEM
• Day-to-day management of wholesale and retail markets
• Monitor usage patterns to forecast electricity demand
AER
Australian Energy Regulator
• Economic regulation / Compliance
• Policies the system
• Monitors the market
AEMC
Australian Energy Market Commission
• Rule maker
• Expert advisory / consultancy

Emission Forensics Complexities





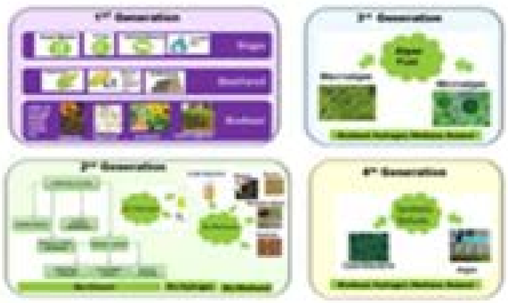




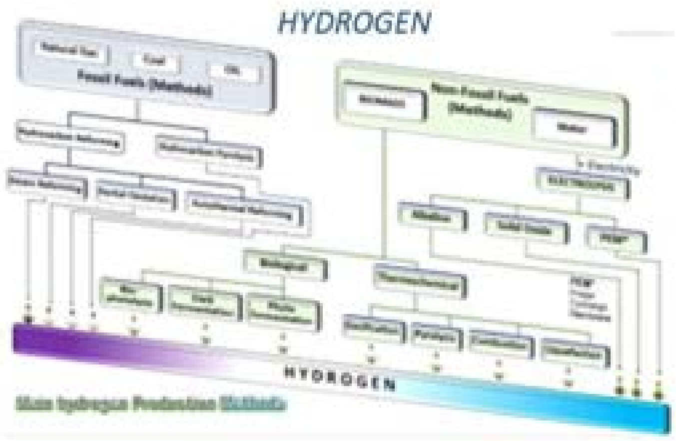
The greenhouse effect is the way in which heat is trapped close to Earth's surface by "greenhouse gases."
These heat-trapping gases can be thought of as a blanket wrapped around Earth, keeping the planet toastier than it would be without them.
GHG effect (warming) effect helps stabilize Earth's atmosphere.
Without CO_2, Earth's surface would be some 33 °C cooler. Life on earth would vanish.
https://climate.nasa.gov/causes/
Potential damage on planet Earth involving:
Climate Change
Ozone depletion,
freshwater availability,
marine life depletion,
ocean dead zones,
forest loss,
Biodiversity destruction,
Recommended Solution:
rising price on carbon emissions that would preclude emissions from most remaining coal and unconventional fossil fuels and phase down emissions from conventional fossil fuels
Human Nature
Competitive nature (aggressive vs cooperative)
Tendency to prioritize comfort, ease, ego, ...
Tendency to prioritize their wishes rather than
Conditioned since birth towards unrestrained consumption
Legislation
Motivates HIGH production @ Low Costs
Motivates large-Centralized-polluted methods
Prioritizes the right of consumption and production and fails on nature
Education
Negligent approach on the use of technologies – provide skills on technologies that will help to deplete the planet faster
Prioritize "innovation" that leads to higher productivity, higher sales, lower costs, and little Concern on the consequences
Faster comms, automation, social media, Apps, al leads to irrational consumption
Political Strategies
Promotion of Regional Develops
Continuous GDP increase, subsides, low price
IPCC helps to mask the greater problem
Paris Agreement, Kyoto Protocol CPS...etc. are inefficient methods
CO2e (Carbon Dioxide Equivalent)
Eco-Sustainability?
Eco-efficiency?
LCA- Life Cycle Assessment
EIA- Environmental Impact
Cradle-to-Grave? Where's the cradle and the grave?
Global Value Chain - GVN
Physical Science
Effects
Measurement
Emissions
Root-Causes
Fossil Fuel
Renewables
DRIVERS
Sources
Thermal
Wind
Fuel-Cell
Biomass
Solar
Householders
Service Providers
Software/Apps/etc.
Technology
Media
Gas Types
Economic Sectors
Countries highest Emissions
Past
1980
Present
Energy Sector 73.2%
https://ourworldindata.org/emissions-by-sector
https://www.aei.org/carpe-diem/animated-chart-of-the-day-top-ten-countries-for-co2-emissions-1965-2019/
https://ourworldindata.org/grapher/cumulative-co-emissions?country=~OWID_WRL
Power Generation + Transmission + Distribution

Renewable Sources – Wide Range of Options

BIOMASS



HYDROGEN



THERMAL