UNIVERSITY OF TECHNOLOGY SYDNEY

# Industrial Energy Efficiency: Exploring Synergies with Industry 4.0 Technologies at Operational Level

**by A S M Monjurul Hasan**

Thesis submitted in fulfilment of the requirements for the degree of

**Doctor of Philosophy**

under the supervision of Associate Professor Andrea Trianni

University of Technology Sydney
Faculty of Engineering and Information Technology

December 2023

## Certificate of Original Authorship

I, *A S M Monjurul Hasan* declare that this thesis is submitted in fulfilment of the requirement for the award of *Doctor of Philosophy*, in the *School of Mechanical and Mechatronic Engineering/ Faculty of Engineering & IT* at the University of Technology Sydney.

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

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature: Production Note: Signature removed prior to publication.

Date: 14/12/2023

## Acknowledgement

I begin by thanking Almighty Allah (The Most Gracious, The Most Merciful) and expressing my sincere appreciation for all that I have achieved.

This Doctor of Philosophy thesis was completed at Faculty of Engineering and IT in the University of Technology Sydney, Australia, between 2020 and 2023. The research funding was covered by the UTS International Research Scholarships and UTS President Scholarship.

Pursuing a doctoral degree is often a long and challenging journey, and it would not have been possible without the support of many individuals. I would like to extend my heartfelt thanks to the following wonderful people who made this journey fruitful and enjoyable.

I am privileged to have Professor Andrea Trianni as my main supervisor during my PhD. Andrea, you have been supportive from the beginning, and I am sincerely grateful to you for sharing your time, knowledge, and guidance throughout my studies. You and your family's kindness and heart for others are truly an inspiration.

I would also like to thank my co-supervisor, Dr. Nagesh Shukla, whose thoroughness and understanding of the field have been a great help. My gratitude goes out to all my co-authors and colleagues. Special thanks to Dr. Mile Katic, for the great times working together.

I would like to express my sincere gratitude to all of my teachers for instilling in me a love of learning and for laying the foundation of my academic journey. Thanks to my friends of Cadet College & IUT, who have been an integral part of my life journey, providing me with support, laughter, and cherished memories that I will always hold. Special thanks to Sabbir bhai & Raihan bhai, who have always been there for me since I moved to Sydney.

I am grateful to my maternal grandparents (boro nanu & choto nanu). Sincere thanks to Bilkis aunty, Azad mama, Manik mama, Shilpi aunty, and Kazal mama - I have no words to express how much love and affection I have received from you since childhood.

My deepest gratitude to my parents for always believing in me. Being raised in a typical middle-class family in Bangladesh, investing in education has never been easy. Despite having a little income, my parents always did their best to ensure my education. Thanks to my younger brother Muhaiminul, whose constant support has been an indispensable source of motivation. Sincere gratitude to my mother-in-law and father-in-law. I am grateful to have you in my life. I would also like to thank Shova apu, Titu bhai, Sonia, and Zayed bhai.

Sazia, you have been amazing in your support and encouragement during my PhD studies. I cannot thank you enough; without your support, I would not have come so far. Thanks to my son Raiyan and daughter Mashiyat, your curiosity about life fills me with happiness.

## Table of Contents

## List of Publications

1. A. S. M. M. Hasan, A. Trianni, “Boosting the adoption of industrial energy efficiency measures through Industry 4.0 technologies to improve operational performance”, ***Journal of Cleaner Production,*** vol. 425, p. 138597, Nov. 2023, DOI: 10.1016/J.JCLEPRO.2023.138597

2. A. S. M. M. Hasan, A. Trianni, N. Shukla, and M. Katic, “A novel characterization based framework to incorporate industrial energy management services,” ***Applied. Energy***, vol. 313, p. 118891, May 2022, DOI: 10.1016/J.APENERGY.2022.118891.

3. A. S. M. M. Hasan, R. A. Tuhin, M. Ullah, T. H. Sakib, P. Thollander, and A. Trianni, “A comprehensive investigation of energy management practices within energy intensive industries in Bangladesh,” ***Energy***, vol. 232, p. 120932, Oct. 2021, DOI: 10.1016/j.energy.2021.120932.

4. A. S. M. M. Hasan, A. Trianni, “A Review of Energy Management Assessment Models for Industrial Energy Efficiency,” ***Energies***, vol. 13, no. 21, p. 5713, Nov. 2020, DOI: 10.3390/en13215713.

5. A.S.M.M. Hasan, A. Trianni, “Towards a Framework to Assess the Impact of Industry 4.0 Technologies & Services on Production Resources”, ***IEEE International Conference on Industrial Engineering and Engineering Management (IEEM),*** 07-10 December 2022, Kuala Lumpur, Malaysia DOI: 10.1109/ieem55944.2022.9989725

6. A. S. M. M. Hasan, M. Raza, M. Katic, A. Trianni, “Towards a Framework Linking Industrial Energy Efficiency Measures with Production Resources”, ***IEEE International Conference on Power & Energy System**,* pp. 856–860, 14-17 December 2021, Shanghai, China. DOI: 10.1109/ICPES53652.2021.9683855

7. A. S. M. M. Hasan, A. Trianni, “Energy Management: Sustainable Approach Towards Industry 4.0”, ***IEEE International Conference on Industrial Engineering & Engineering Management (IEEM)***, 14-17 December 2020, Marina Bay Sands, Singapore. DOI: 10.1109/ieem45057.2020.9309939

**Other Publication:**

8. M. N. I. Siddique, A. S .M. M. Hasan, M. A. Kabir, F. Z. Prottasha, A. M. Samin, S. S. Soumik, A. Trianni, “Energy Management practices, barriers and drivers in developing countries: an exploratory insight from pulp and paper industry”, ***Energy for Sustainable Development***, vol. 70, pp. 115–132, Oct. 2022, DOI: 10.1016/J.ESD.2022.07.015

9. S. R. Hossain, I. Ahmed, F. S. Azad, and A. S. M. M. Hasan, “Empirical investigation of energy management practices in cement industries of Bangladesh,” ***Energy***, vol. 212, p. 118741, Dec. 2020, DOI: 10.1016/j.energy.2020.118741

10. A. Trianni, N. Bennett, R. Cantley-Smith, B. Chen, S. Dunstall, A.S.M.M. Hasan. M. Katic, J. Leak, D. Lindsay, A. Pears, F. Tito Wheatland, S. White, F. Zeichner, “Industry 4.0 for energy productivity: insights and future perspective for Australia”, ***Lecture Notes in Mechanical Engineering, Springer (Accepted)***

## List of Table

## List of Figure

**Abbreviation**

| | |
|---|---|
| EE | Energy efficiency |
| EM | Energy management |
| EnMS | Energy management system |
| IEM | Industrial energy management |
| SEC | Specific energy consumption |
| EEM | Energy efficiency measure |
| IAC | Industrial assessment center |
| ESM | Energy saving measure |
| EMS | Energy management services |
| IEA | International Energy Agency |
| NEB | Non-energy benefits |
| EMP | Energy management practices |
| $CO_2$ | Carbon dioxide |
| HVAC | Heating, ventilation, and air conditioning |
| TAR | Technical asset register |
| CAS | Compressed air system |
| GWh | Gigawatt hours |
| USD | United States Dollar |
| SME | Small and mid-size enterprises |
| GHG | Greenhouse gas |
| SDG | Sustainable development goal |
| I4.0 | Industry 4.0 |
| IR | Industrial Robot |
| AI | Artificial Intelligence |
| IoT | Internet of Things |
| OEE | Overall equipment effectiveness |
| OLE | Overall labour effectiveness |
| CPS | Cyber physical system |
| ISO | International Organization for Standardization |
| EUMMM | Energy and Utility Management Maturity Model |
| EMMM50001 | ISO 50001-based Energy Management Maturity Model |
| CMMI | Capability Maturity Model Integration |
| PDCA | Plan-Do-Check-Act |
| CMM | Capability Maturity Model |
| GHG | Greenhouse Gases |
| SME | Small- and Medium-sized Enterprise |

## Abstract

Energy management is a critical enabler for reducing energy consumption and improved company competitiveness and sustainability. However, its improvement in industrial organizations is hindered by several barriers. Energy management offers multiple benefits beyond energy savings, such as better utilization of production resources, reduced operational costs, improved work environment. Similarly, the emergent industry 4.0 technologies are also claimed to improve efficiency and productivity in industrial processes and decision making. However, so far the potential synergies between industrial energy management and industry 4.0 technologies have been largely overlooked by research. In particular, there is a lack of study exploring the common areas of interaction between energy management and industry 4.0 at the shop floor level, particularly with regard to production resources and operational performance, calling for further in-depth research.

This overarching aim of this thesis contributes to the area of industrial energy management and I4.0 technologies by developing frameworks that decision-makers in industry could use to assess the implication of energy management services (EMS), energy efficiency measures (EEMs) on production resources and operational performance, as well as to understand what impact would industry 4.0 technologies present in enabling or boosting such performances.

To clarify the purpose and organization of this thesis, the structure is based on three main components. First, a qualitative investigation is conducted encompassing energy management practices, barriers, & drivers to energy efficiency, barriers to ESCOs in the energy-intensive industries in a developing economy. The study finds that energy-intensive companies lack comprehensive energy management practices and specialized energy professionals. Inadequate support from higher administration and bureaucratic complexity are major hindrances to energy efficiency. The most significant drivers for energy efficiency are energy cost-saving, rules and regulations, while lack of information is the biggest barrier to consulting energy service companies.

The second component of the thesis is the development of a novel framework to help key industrial decision-makers in making better informed decisions regarding the adoption of energy management activities. This is accomplished by explicitly taking into consideration the characteristics of energy management services based on 25 attributes belonging to four categories such as implementation, impacted area, impact on production resources and productivity. In addition, further light was shed on the practical implementation of energy management activities by also placing focus on the link between the implications of their adoption on production resources and the subsequent impact on industrial operations. The framework is validated by a sample of selected energy management experts within Australian organizations, followed by an application in an industrial context.

The third and concluding pillar of this thesis highlights the role of I4.0 on EEM adoption with respect to production resources and operational performance. In doing this, a detailed framework is developed by integrating EEMs characteristics with production resources and operational performances in the shop-floor, further looking at industry 4.0 technologies for specific EEMs with the impact of production resources and operational performances. For the exploratory investigation in manufacturing companies, EEMs from crosscutting technologies and some industry 4.0 technologies such as Cyber Physical System, Artificial Intelligence, Internet of Things, and industrial robots are selected. By applying the framework, it has been found that leveraging machine data and hardware in a synergistic manner can unlock unexploited benefits beyond energy efficiency, such as improved OEE, labor effectiveness, reliability, and reduced operational costs. The specific case studies also have showed that AI is deemed important for boosting the benefits of programming HVAC and closed cycle process in water management, IoT seems to beneficially affect the adoption of motor systems by improving OEE and reliability.

Despite the specific application, the framework stands out for its unique ability to assess the impact of specific industry 4.0 technologies on EEM at an operational level. This feature is particularly important for industrial decision-makers seeking to identify the potential benefits and challenges of adopting these technologies in their operations. By leveraging this framework, decision-makers can make informed choices on which technologies to invest in and optimize their implementation to achieve the greatest impact on EEM.

Overall, the findings of the thesis represent an exploratory but important step towards energy management and industry 4.0 fields. By doing this study, we wished to highlight several intertwined issues in the field of energy management & industry 4.0 at industrial organizations. The study would benefit both academia and industrial decision makers related to the supply chain of energy efficiency solutions by emphasizing improvement opportunities in their energy management activities.

# Chapter 1

……………………………………………………………………………………………………

*This chapter first presents the general introduction to this thesis. The introduction is followed by aim and research questions, and thesis structure.*

## 1 Introduction

### 1.1 Industrial energy efficiency and productivity benefits of energy efficiency

Embedded within the core of development, energy plays a pivotal role that energizes industries, propels transformative ideas, and steers economic development. This intrinsic interplay between energy and development becomes even more evident while considering the projection of primary energy demand. Spanning the period from 2018 to 2050, a steady and substantial increase of more than 50% is anticipated, predominantly driven by non-OECD economies [1]. Among the various sectors, the industrial sector is expected to account for approximately 8000 Mtoe of final energy consumption by 2050, reflecting a significant 30% surge from the levels observed in 2018 [1]. In fact, the industries accounted for a substantial energy consumption of 170 EJ in 2021, constituting over one-third of the total energy consumed across all sectors and underscoring its significant impact. Nevertheless, this considerable energy consumption carries profound environmental implications, particularly with regard to the industrial sector's substantial contribution to direct $CO_2$ emissions. In fact, the sector's emissions amount to 9 Gt, representing a significant 45% of the total emissions generated by end-users [2].

In this context, ensuring energy efficiency has become a critical element in industrial processes. Energy efficiency serves as a crosscutting strategy for decarbonization and remains the most cost-effective option for reducing greenhouse gas emissions in the near term. Often referred to as the "first fuel" in clean energy transitions, energy efficiency offers swift and cost-effective solutions for mitigating $CO_2$ emissions while simultaneously reducing energy costs and enhancing energy security [3]. In fact, in the Net Zero Emissions by 2050 Scenario, energy efficiency stands as the largest measure to mitigate energy demand, complemented by measures such as electrification, behavioral change, digitalization, and material efficiency across all industries [4]-[5].

In recent times, scholars have increasingly recognized the significant role of energy efficiency in achieving a wide range of outcomes that have a positive impact on industrial processes. It has become evident that energy efficiency not only leads to energy savings but also contributes to various macroeconomic benefits, thereby enhancing overall productivity [6]. These benefits encompass shifts in energy trade balances, improved accessibility to energy, affordability of energy services, reduced air pollution, and fiscal improvements for both national and sub-national entities [7]–[10].

International Energy Agency (IEA) has coined the terms "multiple benefits" or "non-energy benefits (NEBs)" to describe this comprehensive set of outcomes associated with energy efficiency [11]. These NEBs highlight the broader socio-economic advantages that can be achieved through energy efficiency measures. The magnitude of these benefits can be quite substantial, with studies indicating a potential reduction in energy demand by up to 2.5 times through the implementation of energy efficiency measures [11]. Figure 1 presents the NEBs or multiple benefits of EE in industries.

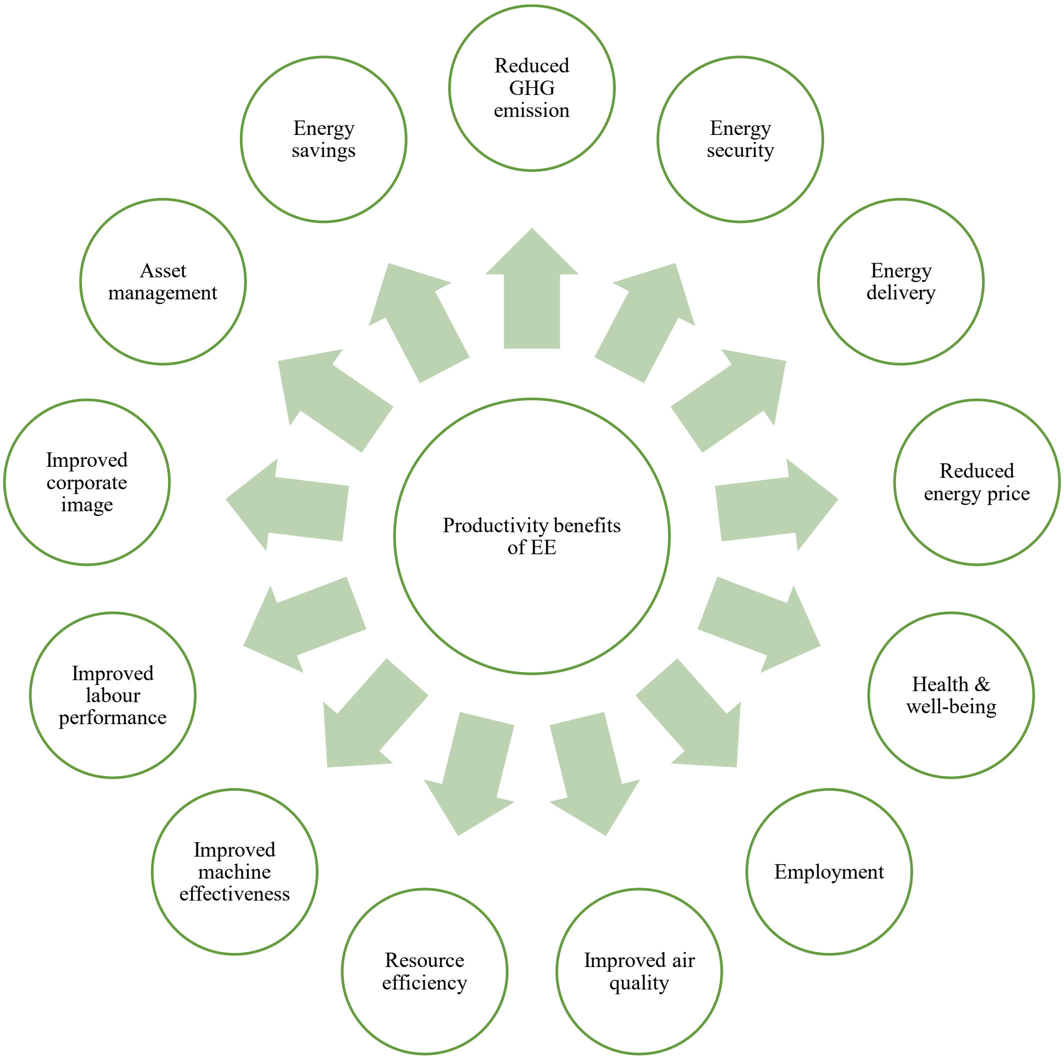


Figure 1. Productivity benefits stemming from EE (adopted from [11])

To date, among the various benefits associated with energy efficiency, only reductions in energy demand and greenhouse gas (GHG) emissions have been systematically measured. However, there is a growing body of evidence that highlights the immense value of the broader benefits in both economic and social terms. These multiple benefits extend to goals that are easily understood and personally relevant to the general public, making them particularly intriguing for policymakers. In fact, positive impacts in these areas hold the potential to generate substantial interest from both the public and policymakers, surpassing the attention typically given to energy savings alone. The added value stemming from these broader benefits acts as a compelling economic and social indicator, capable of igniting a drive towards energy efficiency.

However, despite the myriad of benefits associated with energy efficiency (EE), there has been a notable deceleration in the rate of improvements concerning Energy Efficiency Measures (EEMs) in recent times [12]. This stagnation can be attributed to various barriers [13]-[14], which have contributed to what is known as the “energy efficiency gap” [15], as previously explored in scholarly research [16]-[17]. Extensive studies have been conducted at local, regional, national, and multinational levels to investigate the barriers hindering the adoption of energy efficiency in industrial settings [18]–[22]. Conversely, several studies have also identified drivers that propel the adoption of energy-efficient technologies [23]-[25].

### 1.2 Industrial energy management and energy efficiency gaps

Energy management and energy services are mostly studied through theoretically or conceptually, whilst energy management practices are studied in an empiric way [26]. Academic researchers have conducted studies on energy management practices and their characterization, focusing on various industries such as steel, textile, cement, paper & pulp, foundries, and SMEs [18], [27]-[29]. These studies have delved into a range of topics, including energy management practices, drivers and barriers to energy efficiency, barriers in consulting Energy Service Companies (ESCOs), and strategies for implementing energy-efficient technologies. Through their investigations, researchers have gained insights into the effectiveness of diverse energy management practices and their influence on energy consumption, cost savings, and the overall sustainability of industrial operation.

However, the majority of studies have primarily focused on examining energy management practices within developed economies, leaving a significant research gap regarding the context of developing economies. The unique challenges, opportunities, and dynamics faced by industries in developing economies require specific attention and tailored approaches. Currently, there is very limited research that specifically addresses the energy management practices and requirements of industries in developing economies. Moreover, there has been a lack of integrated efforts to develop a comprehensive assessment model that can effectively guide industrial decision-makers in implementing targeted actions for energy management services. Such an assessment model would provide a structured framework for evaluating the current state of energy management services, identifying areas for improvement, and guiding the selection of appropriate energy management practices and services [30].

Notably to mention that research in this field has highlighted the concept of the "*extended energy efficiency gap*" which encompasses technical and managerial components and reveals a significant disparity between the actual and potential energy efficiency levels in various industrial sectors. Furthermore, there is an untapped market potential known as the "*energy service gap*" attributed to the high operating costs during the implementation phase of energy-efficient measures [31]. However, energy services offer a promising solution for improving energy efficiency in a market-centric manner. By addressing these gaps, researchers and practitioners can develop innovative strategies to optimize energy consumption, enhance operational performance, and achieve cost savings. Closing these gaps will contribute to sustainable and efficient industrial operations, leading to significant energy savings and environmental benefits [32].

Energy assumes a critical role as a production resource within the realm of industrial decision-making, where its cost holds significant importance in the formulation of production plans and strategic initiatives [33]. Therefore, it is essential to analyze energy in relation to other resources within the production system to fully understand its impact on shop floor operations and sustainable manufacturing [34]-[35]. Furthermore, in raising awareness about energy efficiency (EE), it is important to examine the nexus between energy and other production resources [36]. Assessing the impact of enhanced energy efficiency on resource utilization and efficiency beyond energy saving itself is of imperative importance. Research emphasizes the need for better integration of energy efficiency performance within production management [37]. By implementing an integrated performance monitoring system, not only can energy awareness be fostered, but its scope can extend beyond production activities to encompass the overall impact on production facilities. This aligns with previous research conducted on non-residential buildings. Such improved integration of monitoring systems can greatly support companies in their pursuit of ISO 50001 certification and their broader journey towards enhanced sustainability [38]-[39].

Recently, researchers have started to explore the synergies between EE and production resources [40]-[41], However, very little research has been done on industrial energy management services (EMSs), production resources, and production performances inclusively, thus representing a major research gap. Furthermore, the integration of energy management with production systems remains largely unexplored, and there is a lack of comprehensive exploration of incorporating energy management into the industrial decision-making process. Therefore it is imperative to explore the domain of energy management to support industrial decision-makers pointing to the specified actions which are required to minimize the energy management lagging aspects, still keeping mind the multi-dimensional context and complexity of industrial energy management systems [42]-[43].

### 1.3 Industry 4.0 for industrial energy management

The rapid advancements in industrialization have given rise to a paradigm-shifting known as the Fourth Industrial Revolution, often referred to as Industry 4.0 (I4.0). This transformative era marks a significant leap forward in manufacturing and production processes through the seamless integration of cutting-edge technologies. At the core of I4.0 lies the convergence of cyber-physical systems (CPS), Internet of Things (IoT), big data analytics, artificial intelligence (AI), and industrial robotics, empowering industries to achieve unprecedented levels of productivity while offering customization and adaptability [44]-[45]. Industry 4.0 signifies a fundamental transformation in the operational landscape of businesses, revolutionizing how machines, systems, and humans interact and exchange information. The interconnectivity of devices and the ability to collect and analyze vast amounts of data in real-time revolutionizes decision-making processes, enhances operational efficiency, and unlocks new opportunities for innovation and growth. Through intelligent automation, self-monitoring systems, and predictive analytics, I4.0 transforms traditional manufacturing into smart manufacturing, creating agile and responsive production systems.

Notably, energy has played a critical role in driving industrial revolutions and has remained a central focus in the context of globalization. What is particularly interesting is the shared objective between energy management and I4.0, which is to increase efficiency [46]-[47]. Despite their distinct trajectories, both aim to optimize operations and maximize productivity. However, it is crucial to recognize that without the integration of energy management, I4.0 may fail to fully realize its potential and become limited in its ability to leverage the additional features offered by modern technology within industrial settings. By incorporating effective energy management practices I4.0, industries can unlock numerous benefits. Energy management strategies can be seamlessly integrated into smart manufacturing systems, enabling real-time monitoring, analysis, and control of energy consumption. This integration allows for the identification of energy-saving opportunities, improved resource allocation, and enhanced overall efficiency.

Academic literature on I4.0 technologies has predominantly focused on the development of algorithms, models, and hardware, as evidenced by numerous studies [48]–[55]. More recently, scholars have recognized the need to explore the broader implications of I4.0 technologies, particularly in terms of sustainability [56]–[58] and technical perspectives [59]. Studies have also examined the role of I4.0 technologies in supporting operational performance, particularly in the context of energy management and optimization strategies. The literature in this area has expanded, with a focus on topics such as the Internet of Things (IoT) in energy management within production systems, production performance through the integration of big data-based feedback in smart factories [48], [54], [60]–[62].

Despite these efforts, many of these studies have been limited in their empirical evidence, especially when it comes to investigating the nexus of I4.0 technologies and industrial energy efficiency. In particular, the role of I4.0 technologies in driving energy efficiency in industrial settings remains largely unexplored. In fact, very limited studies have looked into the role of specific I4.0 technologies and how it can best leverage the industrial EEMs to improve operational performance. Furthermore, the scientific understanding about the implications of EEMs on production resources and operational performances have not been established inclusively at industrial context, thus representing a major research gap.

## 1.4 Aim and research questions

The thesis aims at exploring the synergies between energy management and I4.0 through the lens of industrial energy efficiency. In doing this, this study first investigates the energy management practices at the industries; second, explores the implications of industrial EMS on production resources and productivity; third, examines the role of I4.0 technologies to improve the performance of specific EEM with the impact of production resources and operational performances.

More in detail, the study has focused to the following research questions:

(I) Research Question 1 (RQ1): What is the status of energy management practices and services in the energy intensive industries? What are the barriers and drivers to efficient energy management in industries? What are the barriers to energy service companies (ESCO) consultation at industries?

(II) Research Question 2 (RQ2): How energy management services are connected to production resources and operational performance at the shop floor? Beyond energy savings, what are the implications of energy management services on production resources and productivity at industrial context?

(III) Research Question 3 (RQ3): What extent the I4.0 can best support EEMs to enhance its performance with the implications of production resources and operational performances? What specific I4.0 technology provides the boost toward the improvement of operational performances?

## 1.5 Thesis organization

The thesis includes three main domains and appends articles as outcomes of three research questions (see Figure 1).

Chapter 1 provides the introduction which discusses the research background, motivation, and overall research objective. Chapter 2 serves as a review of industrial energy management and assessment models in energy efficiency. During the literature review, particular emphasis is placed on exploring relevant frameworks within the industrial decision-making process that encompasses industrial energy management practices & services. The aim is to gain a deeper understanding of the various approaches and methodologies used in this context.

In subsequent chapters, namely Chapters 3, 4, and 5, specific reviews are presented, focusing on individual studies that provide valuable insights into the subject matter. Each of these chapters delves into distinct aspects related to industrial energy management, offering a comprehensive analysis of the existing literature and research in the field.

Chapter 3 focuses on addressing Research Question 1 (RQ1), which delves into the status of energy management practices and services within energy-intensive industries. The main objective is to gain a comprehensive understanding of the current state of energy management in this domain. This involves a thorough examination of the practices and services implemented to enhance energy efficiency, as well as identifying the barriers and drivers influencing their successful adoption and implementation. Notably, a significant gap is observed in the literature, where discussions on energy management practices specific to energy-intensive industries in developing economies are lacking. Consequently, this study stands as a pioneering effort, being the first of its kind to delve into the energy management practices within these industries. Through this exploration, the critical importance of the energy management context is underscored, contributing to an enhanced comprehension of the challenges and opportunities inherent in fostering sustainable practices within these sectors.

Moreover, beyond exploring energy management practices, the chapter takes a closer look at the challenges encountered by energy service companies (ESCOs) while offering consultation services to industries. Recognizing and understanding these hurdles is of utmost importance in formulating effective strategies that foster a conducive environment for ESCOs to thrive and actively contribute to energy efficiency improvements. Adopting a holistic approach, this chapter endeavors to provide a comprehensive view of the energy landscape within energy-intensive industries. In addition, by analyzing the drivers and barriers related to energy management, a thorough understanding of the opportunities and constraints is achieved.

Chapter 4 is dedicated to addressing Research Question 2 (RQ2). The chapter introduces a comprehensive framework designed to support key industrial decision-makers and policymakers in making well-informed choices regarding the adoption of energy management services. This framework takes into account 25 attributes categorized into four key areas: implementation, impacted area, impact on production resources, and productivity. Moreover, the chapter sheds light on the practical implementation of energy management activities, emphasizing the crucial link between their adoption and the subsequent impact on production resources and industrial operational performances. By delving into these essential aspects, this framework offers valuable insights for both academia and industrial decision-makers involved in the energy efficiency solutions supply chain. In fact, it underscores opportunities for improvement in their energy management (EM) activities. Additionally, the framework serves as a useful tool for engineers within industrial organizations, helping them identify and emphasize improvement activities within the energy supply chain system.

In Chapter 5, Research Question 3 (RQ3) is addressed, focusing on the extent to which I4.0 can best support EEMs to enhance their performance, with specific attention to implications for production resources and operational performances at shop floor level. More importantly, a novel framework is developed that investigates the relationship between a subset of I4.0 technologies and EEMs within selected manufacturing enterprises. In terms of scholarly contribution, the framework and its associated empirical exploratory investigation address a critical gap in the existing literature. In fact, to the best of the author's knowledge, this study represents the first of its kind to highlight the nexus among I4.0 technologies, EEMs, production resources, and operational performances within an industrial context. The findings from this investigation provide valuable insights into the potential benefits of integrating I4.0 technologies to enhance EE and optimize operational performance. By understanding the dynamic relationship between I4.0 and EEMs, industry leaders are equipped with essential knowledge to leverage the technologies effectively, driving improvements in operational performance and achieving energy efficiency within their respective sectors.

Chapter 6 serves as the culmination of this thesis, providing a comprehensive summary and concluding remarks. It offers a cohesive overview of the key findings, insights, and contributions made throughout the research. In addition to the summary, Chapter 6 also outlines future research directions, identifying areas that warrant further exploration and investigation. These future research directions aim to fill gaps in knowledge, address emerging challenges, and build on the foundation established by this thesis.

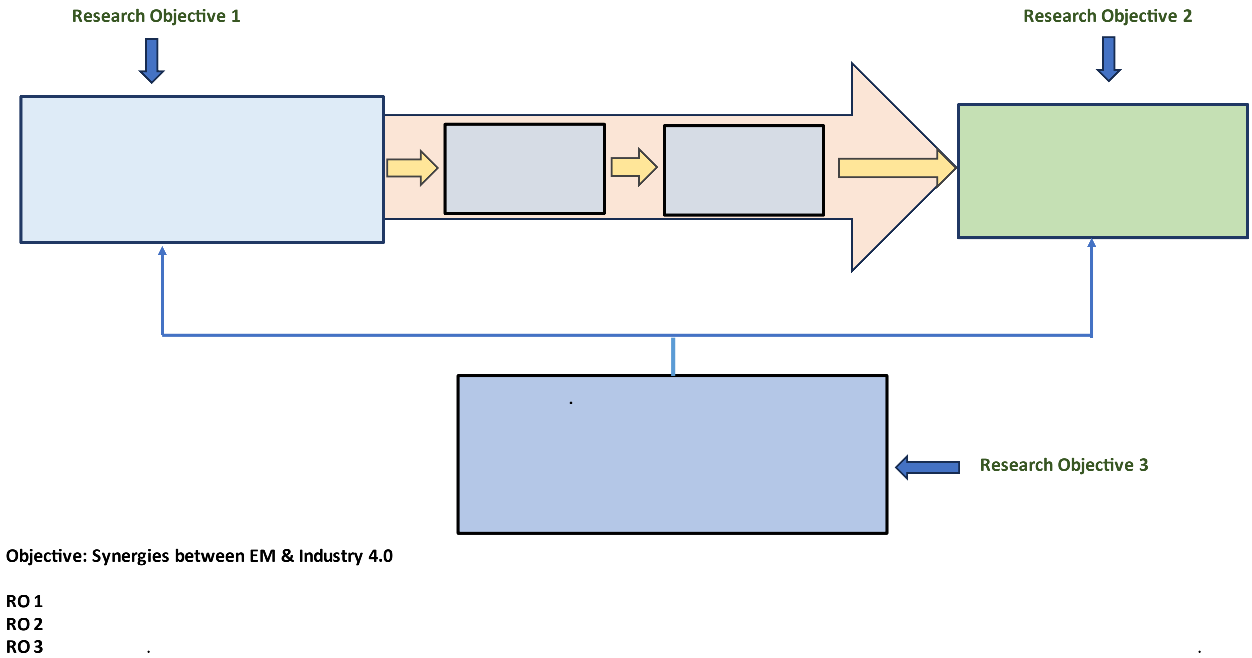


Figure 2. Graphical framework of this thesis

# Chapter 2

………………………………………………………………………………………………………………

*This chapter discusses the definition of industrial energy management, and approaches to industrial energy management. In describing the approaches to industrial energy management, minimum requirement, maturity models, energy management matrix, and energy efficiency measures characterization frameworks are highlighted followed by discussion.*

*This chapter is published in the following conference proceedings and journal:*

*(i) A. S. M. Monjurul Hasan and A. Trianni, "Energy Management: Sustainable Approach Towards Industry 4.0," in 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2020, Marina Bay Sands, Singapore. DOI: 10.1109/ieem45057.2020.9309939.*

*(ii) A. S. M. M. Hasan, A. Trianni, "A Review of Energy Management Assessment Models for Industrial Energy Efficiency," Energies, vol. 13, no. 21, p. 5713, Nov. 2020, DOI: 10.3390/en13215713.*

## 2 Review of industrial energy management assessment models

### 2.1 Industrial energy management definition

Defining energy management is significant when it comes to the point at energy management modelling or energy system practices implementation. Energy management concept is specified by many studies that incorporate multiple arenas. The prime areas covered by multiple studies to define energy management are energy consumption, strategic aspect, the involvement of managerial perspective, and people relevancy (see Figure 1) [26].

The German Federal Environment Agency defined energy management as the inclusion of planned and execution of actions to ensure predefined performance by a minimum amount of energy input [63]. B.L. Capehart has characterized the term energy management as the proficient and effective usage of energy towards maximization of profits and increasing reasonable positions [64]. O'Callaghan et al., defined the energy management as the application of resources in regards of supply, conversion and utilization which integrates monitoring, measurement, archiving, critical examination and analyzation, control and rerouting of energy as well as material flows through the systems for ensuring minimal energy usage and achieve meaningful goals [65].

To define energy management, Bunse et al. focused on the inclusion of control, supervision and improvement activities towards energy efficiency [37]. On the contrary, Ates et al. strengthened on the combination of techniques, activities, and managerial processes that leads to reduce energy cost and anthropogenic emissions [66]. One of the studies by Abdelaziz et al. promoted energy management focusing on energy optimization strategy that incorporates compelling the energy demand [67]. A comprehensive definition of energy management has been proposed by Schulze et al. that incorporates all necessary energy management elements and energy management practices in the industries [43].

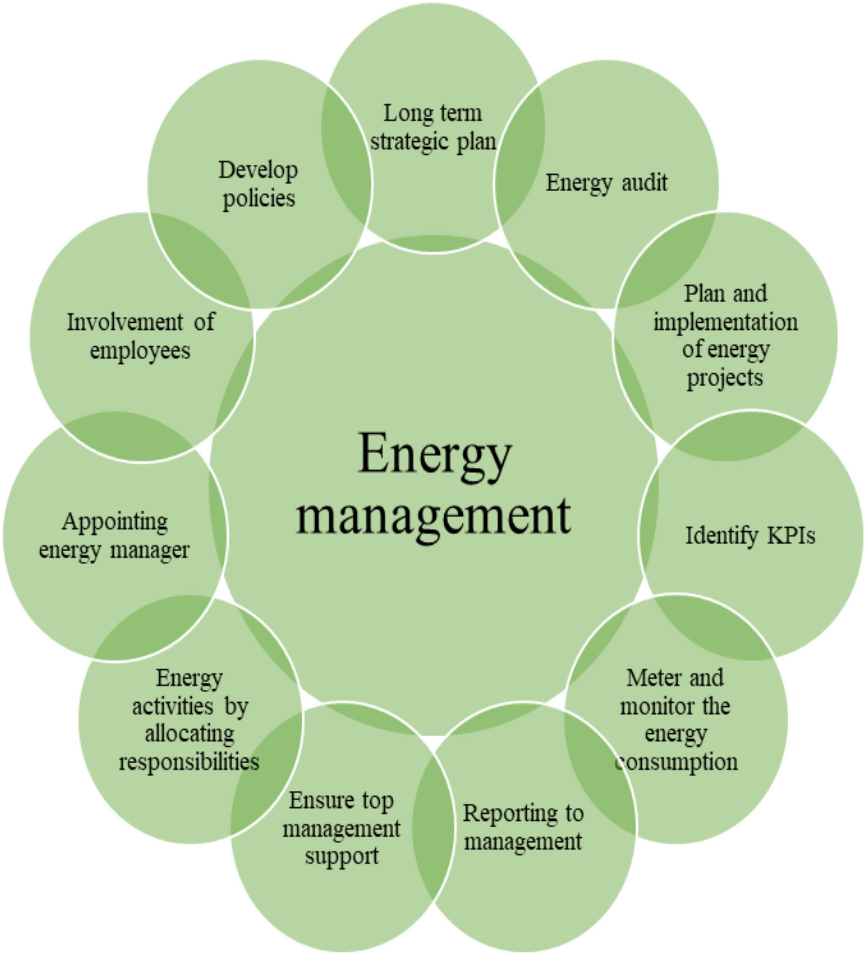


Figure 3. Key factors for successful energy management system [18], [28], [66], [68]

In academic literature, energy management is portrayed as a holistic combination of applying resources, conversion and application of energy [19], [23], [26], [43]. The system involves checking, auditing, recording, scrutinizing, and more importantly controlling the energy flows to ensure the minimum consumptions of energy but to achieve maximum energy productivity [19], [69]. Academicians have pointed some of the minimal prerequisites for implementation and operation of energy management in the industries [67], [66], [70], [28], [68]. Table 1 (adopted from Schulze et al. [43]) illustrates the requirements toward energy management with specifications whether the requirements are considered full, partly or not under consideration.

Table 1. Minimal prerequisite for energy management in industries

| Minimum Prerequisite | Abdelaziz et al. [67] | Christoffersen et al. [68] | Thollander and Ottosson [28] | McKane et al. [70] | Ates and Durakbasa [66] |
|---|---|---|---|---|---|
| Long-term strategic plan; inclusion of energy policy; energy saving targets. | ✓✓ | ✓ | ✓✓ | ✓ | ✓ |
| Energy activities by dedicated responsibilities & actions | ✓ | ✓ | × | × | × |
| Acquaintance of energy management team led by the energy manager | ✓✓ | × | × | ✓✓ | ✓ |
| Policies and proceedings | × | ✓ | × | ✓✓ | ✓ |
| Energy audit to explore energy-saving features | ✓✓ | × | ✓✓ | × | × |
| Planning & implementation of an explicit energy-saving program | ✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| Identification of key performance indicators | × | × | × | ✓✓ | × |
| Meter and monitoring of energy consumption | ✓ | × | ✓✓ | × | ✓ |
| Energy reporting | ✓✓ | × | × | ✓✓ | × |
| Top management commitment | × | × | ✓✓ | × | × |
| Employee engagement in energy management activities | ✓ | ✓ | ✓ | × | ✓ |

*Abbreviations: ✓✓(Full Consideration); ✓ (Partial Consideration); × (Not Considered).

It becomes discernible by analyzing the minimum requirements for energy management from table 2 that the sets of minimum requirements elucidated in the studies contrast in the number of elements as well as conformation of the individual features. Besides, it relics indistinctness on the conclusiveness of the list of minimum requirements whether it is suitable to describe a fully developed energy management. By analyzing earlier contributions on the topic, we can note the lack of a comprehensive conceptual framework about energy management. Therefore, in this thesis, this research gap is responded by complying a review of academic journal publications in the area of industrial energy management and use its results to propose future research avenues to explore further.

### 2.2 Approaches to energy management models

There are research streams which are considered in academia as well as the industries to assess the energy management models. The streams can be categorized as "Minimum requirements", "Maturity models", and "Energy management matrixes" [26]. Furthermore, there is assessment tool namely "Energy Management Measures Characterization Framework", so to shape the energy management aspects accordingly". This is practice based, therefore basing on energy management practices with characteristics.

#### 2.2.1 Minimum requirements

The ISO 50001 standard that deals with energy management issues is incorporated at the first stream and thus apprehends guidelines to enable energy management system [71]. Enabling the organizations towards energy efficiency is the primary purpose of ISO 50001 Energy Management System standard. The standard is reviewed and published by the ISO/TC 301 Technical Standardization Committee, Energy Management and Energy Saving in 2018 [71]. The protocol has a high level of hierarchical structure consists of ten chapters with a homologous architecture. The ISO 50001 standard is a consistent improvement framework which consists of "Plan-Do-Check-Act" at organizational practices.

Table 2 presents the phases that are comprehended at ISO 50001 Energy Management System standard [71]. However, it does not apprehend the critical assessment of the enterprises' effectiveness for a taken initiative of particular energy management practice. Besides, the initial stream incorporates primary endeavor to evaluate energy management, maintaining the limit of analysis [66], [68].

Table 2. The continual phase of ISO 50001 Energy Management System Standard

| Phase | Remark |
|---|---|
| Plan | To apprehend the organizational context; incorporation of energy policy; incorporation of energy management team; consideration of actions towards risks and opportunities; conduct of energy review; identification of significant energy uses & establishment of energy performance indicators; energy baseline; objectives & energy targets; necessary action plans to improve energy performance in accordance with the organization's energy policy. |
| Do | Implementation of the action plans; operation & maintenance controls, and communication; ensuring competence in energy domain i.e. energy performance in design & procurement. |
| Check | Monitor; quantify; analyzation; evaluation; audit & conducting management review of energy performance as well as energy management system. |
| Act | Activities to address non-conformities and continuation for improving energy performance. |

#### 2.2.2 Maturity models

This second stream solicits a systematic perspective for assessing energy management in the organization [72] that includes the analysis for the requisite steps to enact energy management system

[73]. Continuous improvement options are one of the significant features of maturity model. Therefore, the maturity model is accepted and popular in academia as well as industries since the development of the Capability Maturity Model (CMM) [74], [75], [76]. The maturity models help the institutional enterprises surmount the austerity and enhance the quality by measuring institutional maturity based on particular or multiple domains with the help of predefined rules [77], [78]. . However, the maturity models are single dimensioned that focus either on objects maturity or process maturity, whilst the process maturity levels are dominant than the object-based model [79]. In one of the studies, Bojana et al. presented the maturity stages of energy management at activity levels [80]. Figure 4 (Source: [81]) exhibits the levels considered in maturity models for energy and utility management.


Figure 4. The levels in maturity models for energy & utility management

**2.2.3 Energy management matrixes**

The Energy Management matrixes are incorporated with the third stream [82], [83] that confer multiple similarities with the maturity model. It offers an insight into the present approach to energy issues in a company and helps the management to improve energy efficiency by integrating feedback. It also shows the substantial improvement potential in energy efficiency that is achievable by technical activity alone. However, the application of the energy management matrix in a wider range of industrial organizations has acknowledged manifold activities towards improvement of energy management practice. In addition, it puts the hitherto isolated technologically-based attempts to improve energy efficiency in a more effective management framework, often for the first time. The high standpoint from an analytical perspective, maturity concept conversion into a sophistication level along with a self-appraisal approach based on organization’s perspective are the common points of energy matrixes with maturity models. Hence, no additional benefits are provided from these models in terms of approaches and aspects considered for reasoning. However, introducing assessment models have brought an amelioration that incorporates detailed activity list considered as energy management practices, whilst critical factors have not been addressed for evaluation [83], [84].

**2.2.4 EEMs characterization framework**

The EEM characteristics are delved by the fourth research stream [85]. The energy efficiency measures characterization framework is important to formulize in the context of information sharing both for the policy and decision-makers about energy efficiency measures. Thanks to improved knowledge and information on industrial energy efficiency measures. Indeed, the policymakers could have enhanced support to develop the operative policies for endorsing energy efficiency at the industries. In addition, the improved knowledge on energy efficiency measures characteristics can articulate in-depth comprehension of the bottlenecks that hindering the implementation of energy efficiency processes [86]. Indeed, this is an interesting fact for resolution and policy makers.

Fleiter et al. exhibited detailed and thorough narratives of characterizations that facilitated understandings of the endorsement process for EEMs [85]. The framework encompasses twelve diverse features of energy efficiency measures which are emanated from the field of technical, relative advantage, and informational perspective. Worrell et al. characterized and grouped the energy efficiency measures into multiple attributes such as waste, emission, operation & maintenance, productivity, working environment, and other, where the secondary benefits are listed [7]. On the contrary, Trianni et al. devised a framework to explore energy management practices [86]. An inclusive view on energy efficiency measures integrating the recent applicable perspectives is encompassed in this framework for industrial decision-makers. Nonetheless, analytical factors of energy management activities are not portrayed comprehensively. Lung et al. affirm about the impact of additional savings & productivity benefits stemming from energy efficiency initiatives resulting in more compellingly. The authors focused on the methodology to characterize the attributes of productivity benefits as well as ancillary savings into a payback forecasting framework [87].

Another model has been proposed in a contemporary study by Trianni et al. in the domain of characterization framework to assess industrial energy management, focusing on the benchmarking of energy management practices [26]. In this model, three elements have been considered that are energy management practice lists followed by specific baseline for benchmarking the performances and optimal threshold adoption in the assessment. The notable aspects of this model are the energy management practice adoption evaluation and more comprehensiveness output compared to the other models. More importantly, it features elaborate energy management approaches and capabilities assessment to an indistinct evaluation of energy management practices. On the contrary, Sorrell [88] and Benedetti et al. [89] have considered three-dimensional classification framework focusing to energy service contracts. The framework of Sorrell is customer perspective based and consisted of "Scope", "Depth" and "Finance" dimension. Benedetti et al. considered "Scope", "Intangibility of the Contract", and "Degree of Risk".

The synopsis of the existing management assessment models is presented in Table 3

Table 3. Synopsis of the existing energy management assessment models.

| Category | Model Narration | Remark | Reference |
|---|---|---|---|
| Minimum requirements | Significant features: energy policy, energy saving goals (quantitative) or aspirations regarding energy-saving projects and their implementation. Energy efficient purchases, specific allotment of energy responsibility & tasks. Functioning engagement of stakeholders, specially the employees by apprising, persuading and educating. | This model consider the energy management as a comprehensive management system. Focused on policy, energy saving goals and specific energy saving projects. However, the model does not integrate the energy manager concept. Furthermore, there is no clear guideline about top or mid-level management support to achieve energy savings. Though, involvement of employee to energy saving related work are suggested. | [68] |
| | PDCA cycle is the basis for instructions. Preconditions: management liability; policy; legitimate concern & obligations; energy audit; energy performance index; energy baseline; energy targets, and energy management blueprint; proficiency, training & consciousness; communication; archiving; energy services acquisition; operation & control; monitoring, measurement & analysis; compliance evaluation maintaining the legal necessities; in-house audit of the energy management system; aberration, corrective as well as precautionary action; archive governance; management review. | ISO 50001 incorporates nineteen characteristics in the framework. Precisely, management commitment and energy manager are also inclined to the model. Moreover, the framework integrates the employee involvements and documentation and records for further assessment. | [71] |
| | Alteration of the merest requirements from the (27)'s set by adding the metering of major proceedings; inclusion of dedicated energy manager at the industry. | This model is an extended version of Christoffersen et al. [68]. The model integrates energy metering, energy policy, energy manager, saving target and saving projects focusing on energy. | [66] |
| Maturity models | Five stages: preliminary, arrange, delineate, managed in quantitative form and reformed; Novel process avenues are regulated towards progress focusing on environmental aspect; Four maturity phases: practice enactment, standardization of practice, performance management and recurring phase for improvement. | The model used CMMI as a reference framework and extended to environmental management context. It comprised of particular procedures for energy as well as resource management. No clear guideline about dedicated energy manager. | [81] |
| | Instructions to attain improved energy efficiency & amenability with energy management standards especially ISO 50001. Energy management actions are | The framework adapts manifold energy management practices based on PDCA cycle. Notably, top management support is incorporated in the framework. Energy | [90] |

| | | | |
|---|---|---|---|
| | categorized into five maturity phases subsequent to the PDCA cycle. | management roles are characterized. However, no clear indication about energy manager inclusion in the process. | |
| | Five levels: Emerging, Define, Integration, Optimization & Novelty; four sections on the basis of PDCA cycle, 16 pillars & 63 sub-pillars. The model allows 5 attribution promulgation for each sub-pillar to evaluate the maturity. | Energy management review along with action plan are integrated to the framework. In addition, competence building feature is also included. | [91] |
| | Primary features for the energy consumption management keeping alignment to ISO 50001. Five phases: initial, intermittent, planning, supervisory & optimal. 5 dimensions that are portrayed as requisite for success: consciousness, information and expertise (utmost significant); methodological proposition; energy performance management and archiving system; institutional architecture; alignment with strategy. | The tool is not incorporated with inclusion of energy manager. | [72] |
| | Incorporation with ISO 50001; knowledge base creation for self-assessment along with monitoring & improvement. The levels are depicted for each ISO 50001 process instilled by Eric et al. [81]. | The assessment tool includes top management commitment, and energy manager appointment with other manifold energy management practices. | [80] |
| | Salient features are the assessment of compelling factors for energy management adoption, contribution towards a better understanding of suitable energy management configuration with the help of evaluation of maturity level. | The model considers inclusion of energy manger, precisely a dedicated energy management team. In addition, top management support is integrated with the considered attributes in the model. | [73] |
| | Incorporation of qualitative metrics; assessment model implies on PDCA cycle; inclusion of SWOT analysis tool, incorporation of global energy management team and external peers. | Incorporates there application specific purposes which are descriptive, prescriptive, and comparative. Features with manifold energy management practices along with energy manager. | [92] |
| | Consists of three features: (1) energy efficiency features (2) energy efficiency maturity levels; (3) implementation method which is accustomed from ZED scheme especially for SMEs. Seven dimensions: management obligation, arrangement and procedure, compliance of regulation and fiscal enticements, archiving system, product & procedure innovation, in-house communication, and ethos. Consists of nineteen characteristics. | Total number of nineteen energy efficiency characteristics are integrated in the model. In addition, management commitment is segregated into two sections in the form of strategic priority and energy policy. | [93] |
| | Five levels of energy management matrixes to address six institutional aspects that are policy, organization, | Top management support is fully integrated into the framework under | [94] |

| | | | |
|---|---|---|---|
| | motivation, information scheme, marketing & financing. | policy section. Energy managerial role included in organizational structure. | |
| | Five levels of energy management matrixes to assess six institutional issues that are energy management scheme; organization; staff inspiration; tracking, supervision & reporting systems; staff consciousness/ training & promotion, and financing. | Energy manager feature is integrated with a proposition of organizational structure. Moreover, energy management is considered comprehensively in this framework. | [82] |
| Energy management matrixes | Five levels of energy management matrixes to assess six institutional issues which are policy or specific guidelines, coordinating, training, evaluation of performance, communication, and financing. Valuation model exploring the subsequent aspects reflected as energy management practice: policy & legislation, energy blueprint, organizational formation; regulation; acquisition strategy, financing scheme, observation & analysis of energy consumption, setting of goal; identification of possible options; staff involvement & training; operational process; communications. | The CarbonTrust guidelines comprised of five aspects. Inclusion of dedicated energy manager is not integrated to this model. However, the model incorporates senior management commitment to enhance energy efficiency related initiatives. | [83] |
| | Model exploring the succeeding features considered as energy management practice: energy director appointment, incorporation of energy team, apply of energy policy; collection of information & management, establishment of yardstick or threshold, analysis, assessing from technical perspective and energy audits; exploring and setting the scope, improvement option estimation, goal setting; define technical procedures and targets, roles & resources determination; formation of a communication plan, awareness raising, capacity building, inspire, trail and monitor; measurement of result, recapitulation of action plan; maintain internal recognition, and receiving external appreciation. | The ENERGY STAR guideline clearly emphasizes on appointment of energy director with dedicated energy team. In addition, the model looks to establish baselines for measuring energy performance. | [84] |
| EEMs characterization framework | Three main characteristics are considered. Each characteristic are divided into sub-divisions. The first character "Relative advantage" is attributed by internal rate of return, introductory expenses, reimbursement time, and benefits of non-energy. "Technical context" the second character is attributed by modification type, impact opportunity, gap among core processes, and Lifetime. The last character "Information context" is attributed by transaction expenses, planning and | One of the salient features of this framework is inclusion of non-energy benefits. Energy manager is not integrated into the framework. | [85] |

| | | | |
|---|---|---|---|
| | execution knowledge, Dissemination progress, and field wise applicableness. | | |
| | Economic characterization consists of payback time, application costs. Energy is attributed with resource stream and energy saving. Environmental characterization is attributed by waste minimization and emission contraction. Production is attributed by productivity, working environment, and operation & maintenance. Implementation related attributes are energy saving strategy, types of action, implementation easiness, success probability, community engagement in corporate level, distance among key processes, and audit regularity. Interaction-related characterization is attributed by indirect effects. | Corporate involvement is one of the notable attributes and considered as significant for industrial decision-makers. The need for analyzing energy efficiency measures as per different perspectives is highlighted; precisely having the aspects in grouped for providing more inclusive view on the pertinent outlooks distinguishing the energy efficiency measures. | [86] |

### 2.3 Discussion

The energy management frameworks were mainly researched to adopt energy management practices at the technical levels in the industries. However, the reviewed studies emphasized the energy management system, ISO 50001, and PDCA cycle, while some studies suggested holistic approaches towards industrial energy efficiency.

The framework proposed by Christoffersen et al. was stood out on the Danish industries and emphasized on multiple factors, mostly energy policy, goals and capstone projects aimed at energy savings. Regulation, external relations, company characteristics and organizational internal condition are the main out-layers of the model to frame the energy management. However, the company size and energy intensity are two factors that can be considered to categorize the industries to apply or analyze the model [68]. The main features proposed by Christofferen et al. aligns with ISO 50001: 2011 standard though this model has been replaced by ISO 50001: 2018 [58].

The earlier model encompassed energy management system implementation based on PDCA cycle and enlisted few prerequisites that include mainly management liability, policy, energy audit, energy performance indexing, energy management blueprint, documentation and so forth. One of the major changes in the recent model is the PDCA cycle modification. "Checking" was the center in the earlier version, whilst "Leadership" became the focus of all cycle components. Figure 5 (adopted from [71]) represents the revised PDCA cycle of ISO 50001:2018. In the minimum requirement segment, the model proposed by Ates et al. comprehended conventional streams towards energy management. One of the significant features is the inclusion of energy manager, whilst ISO 40001 (environmental permit) also act as an enabling feature along with ISO 50001 [66].

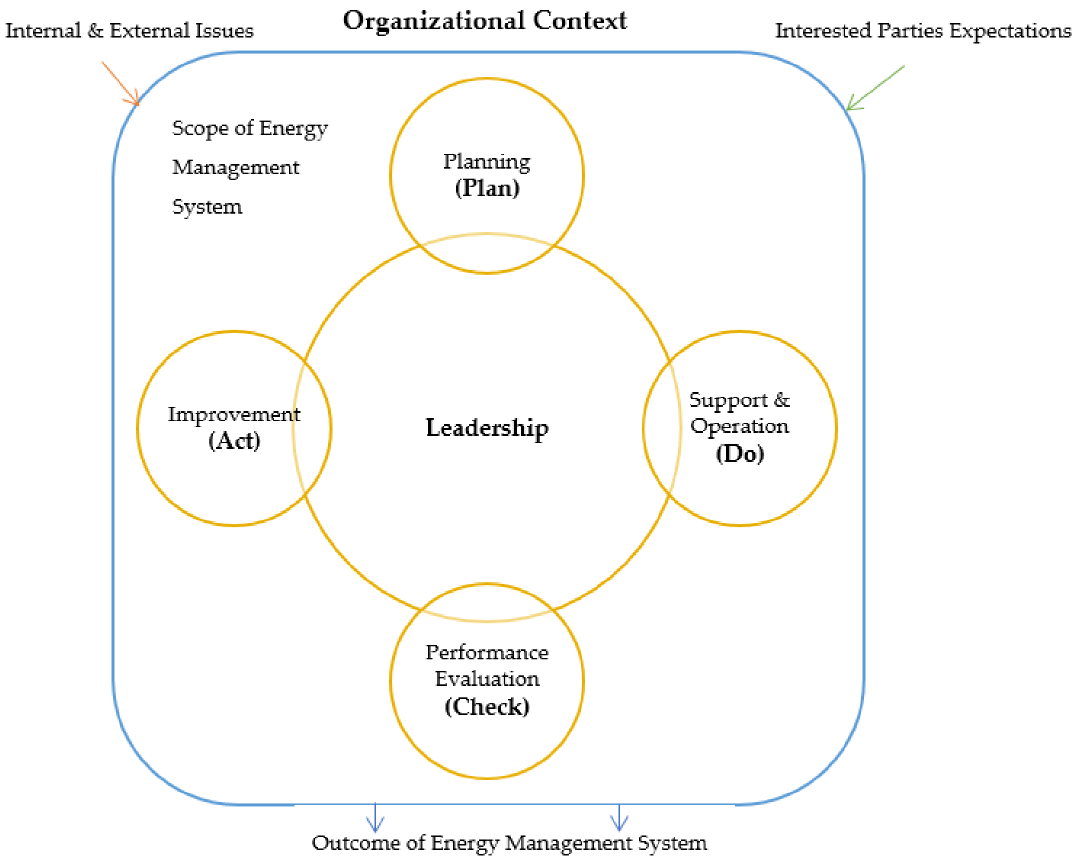


Figure 5. The PDCA cycle adopted in ISO 50001: 2018

Looking at the minimum requirement focused model, it is observed that all the energy management initiatives are not integrated into the frameworks. Christoffersen et al. [68] considered energy management as a comprehensive management system. However, the model does not integrate the energy manager concept. Furthermore, there is no clear guideline about top or mid-level management support to achieve energy savings. Though, the involvement of employee to energy-saving related works are suggested. Nonetheless, The ISO 50001 model is a significant protocol [95] along with the proposition by Ates and Durakbasa [66], manifold aspects are still to be explored regards of operational activities in the industrial energy management domain. For instance, the principles of sustainability and integral management need to be presented at the protocol. In addition, there is very little contribution on the risk management and opportunities of energy efficiency from an integral and strategic point of view, including the planning and control of product lines, process design, projects, and business approaches [95].

Notably, the fruitful operation of the energy management system requires the integrated deployment of planned, tactical and operational levels that align the business culture with sustainable attainment. In this context, the vision that the organization plans to form should be linked to energy efficiency strategy with organization's survival plan in the market. Additionally, it is necessary to make explicit reference to newly adapted technical features through peer to peer energy management platform for optimizing the integration of energy management system component with the variable energy demand [96], [97].

Moreover, an integrated perspective to control of operational features of each process are required to explore linked to energy efficiency [95].

In the energy management maturity model segment, the model proposed by Ngai et al. based on capability maturity model integration (CMMI), an extension of capability maturity model incorporated five levels according to the behavioral exhibition of the industries [81]. The levels are determined by performance area of key processes [98]. The achievement goals of key process areas must be specified for individual level for further actions. Notably, the propositions of CMM framework has been applied at multiple process enhancement programs in order to achieve the desired quality in the production system [99]. One limitation of this model is inadequate implementation time, having only one factory for consideration. However, the authors have affirmed the acceptability of the model because of prior implementation of management practices. On the contrary, Antunes et al. emphasized the PDCA cycle to design the energy management framework [90]. Additionally, the authors implied the model with ISO 50001 and incorporated energy management practices also. Notable to mention that Finnerty et al. also designed the framework based on the PDCA cycle, keeping on focus on energy management practices [92].

The model proposed by Introna et al. is comprised of five dimensions and enables the feature of self-evaluation for the industries towards energy management practices. The dimensions are characterized by identifying the necessary elements in energy management consumption segment of the industries [72]. On the contrary, Jovanović et al. focused on ISO 50001 processes as well as PDCA phases, keeping the knowledge base in the model EMMM50001 [80]. The EMMM50001 establishes the relation to EUMMM maturity levels, maintaining ISO 50001 specifications and PDCA phases. Notably to mention that EMMM50001 links the CMMI criteria, also maintaining the ISO 50001.

It can be observed that the majority of the maturity models emphasized on similar type of characteristics and areas to evaluate the energy management in an organization by a systematic set of commendations. However, the narrated models demand more time and resources to perform as per their characterization. In addition, looking at the scientific literature, all of the frameworks studied to see the requirements for providing a continuous development path following the PDCA approach and ISO 50001. Notably, few of the maturity models incorporate the implication of dedicated energy manager and top management support. In contrast, Antunes et al. [90] affirm on top management support whilst not integrating the energy manager in the framework. The framework by Introna et al. [72] also not complied with the energy manager. Nonetheless, Jovanović & Filipović [80] and Finnerty et al. [92] considered top management support along with the energy manager in their framework.

Gordic´ et al. applied the energy management matrixes model in the Serbian car manufacturer industries and critically analyzed the existing energy management system with the model [82]. Notably to mention that the energy management matrixes models proposed by Gordic´ et al., Carbon Trust, and Energy Star are encompassing all key areas to assess the energy management practices in the model, with having few modifications at the individual version.

On the contrary, Fleiter et al. [85] and Trianni et al. [52] emphasized on characterization based model where both of the models are incorporated with specific attributes. The characterization scheme has some implications on policy design and assessment. However, formalization of the groups with categorized attributes enables the option towards relevant aspects identifying the energy efficiency measures. Besides, Trianni et al. contend a comprehensive scenario on EEMs focusing on the relevant aspects of industrial energy management [52]. One of the critical factors, "corporate involvement" for industrial decision-makers is also implied, hence allows additional feature and increase the applicability of the model. However, the authors acknowledge more compatible space for the SMEs within the model, as SMEs are sought to be entitled to more attention considering their cumulative energy consumption percentile [100].

In a recent study, Tina et al. persuade the significance of SMEs and the policy implications in the peripheral of the industrial energy sector [100]. Referring to the SMEs, Prashar [93] proposes an energy efficiency maturity assessment framework that emphasizes on SMEs. Notably, the author argues that the common energy efficiency framework approach does not facilitate fully to the SMEs; hence customized maturity framework is significant. The author considered steel re-rolling mill sector of India as the contextual sphere for the proposed framework.

Few of the studies on characterization the energy efficiency measure focuses on financial features. Notably to mention that these models do not frame the energy efficiency measures comprehensively, rather offer some framework without characterizing the energy efficiency measures in-depth. In one of the studies by Pye and McKane states that quantification of the accumulated benefits of energy efficiency scheme supports the enterprises perceive the monetary opportunities of EEMs financing [101]. The energy savings features act not as the singular primary driver for the industrial decision process; hence the authors persuade on energy savings to be viewed as a factor of the holistic approach towards energy efficiency programs.

Skumatz studied the methods to find out the attributes of EEMs and established the scheme to measure both of the positive and negative secondary benefits stemming from industrial energy efficiency schemes [9], [102]. On the contrary, Mills and Rosenfeld provided a framework to understand multiple benefits of energy efficiency initiatives and grouped the attributes into the better interior environment, noise lessening, savings of labor & time, improved supervision of procedure, convenience, water savings and waste reduction, and benefits due to downsizing of equipment [103].

The majority of studies on energy efficiency measures, benefits, and initial characterization frameworks propose few interesting reflections. However, a lack of consistency on the attributes grouping within existing categories from the methodological perspective is observed. It is found that the same attributes are grouped in different categories by different researchers. Moreover, the attributes are categorized and then aggregated again within other segments by different researcher. For instance, “reduced noise” & “improved indoor environment” are framed in two different categories in [103], whereas “reduced noise level” as categorized in “working environment” segment.

On the other hand, the decision-making process is a grey area keeping mind about the stakeholders. Nonetheless, the earlier characterization framework did not incorporate the energy efficiency measure implications in a comprehensive way. To be precise, the inclusion of non-energy benefits is not incorporated into the characterization framework. Notably, the inclusion of non-energy features in the modeling factors would double the cost-effective potential for energy-efficiency enhancement, likened to an analysis eliminating those benefit [7]. However, few attributes (e.g. improved air quality, better worker safety, reduction of noise level, and improved working situation) are there in the characterization framework, which are difficult to quantify [102]. Therefore, speculation is required to articulate the benefits into a comparable cost figure, and hence the assessment turns out to be rather subjective [7].

The study by Ngai et al. [81] features energy management with particular process areas in the manufacturing industries. In this study, few guidelines are offered to conduct analysis for organizational maturity improvement in terms of energy along with the management of utility resources. However, the integration of energy management into production process has not complied comprehensively. This is a significant avenue that needs be to address with utmost attention in future studies considering the technical implications offered by Industry 4.0. Notably to mention here that increasing the efficiency at the production processes is one of the salient features of Industry 4.0 [104]. The deployment of smart machinery offers diverse benefits which primarily includes manufacturing productivity and waste reduction [105]. Therefore, it is worth observing the energy management characteristics linked with production process through the lens of Industry 4.0.

Nonetheless, energy management towards industrial energy efficiency has been widely discussed in academia, and several barriers are still persistent in the energy management domain. The identification of barriers is important because it hampers or slows down the adoption of energy efficiency measures [106]. Several studies have addressed the barriers which cover energy-intensive industries to SMEs and include regional, national and transnational perspectives [18], [27], [28], [107]–[110]. However, most comprehensive studies focusing on energy management have been discussed without really looking at the integration of energy management into production and operation management. An imperative avenue, therefore, lies to be further explored in future within this research domain.

# Chapter 3

…………………………………………………………………………………………………………

*This chapter discusses energy management practices in energy intensive industries, barriers and drivers to industrial energy efficiency measures, and barriers to energy service companies (ESCO).*

*This chapter is published in the following journal:*

*A. S. M. M. Hasan, R. A. Tuhin, M. Ullah, T. H. Sakib, P. Thollander, and A. Trianni, "A comprehensive investigation of energy management practices within energy intensive industries in Bangladesh," Energy, vol. 232, p. 120932, Oct. 2021, DOI: 10.1016/j.energy.2021.120932.*

## 3. Investigation of energy management practices within energy intensive industries

### 3.1 Introduction

After maintaining a Gross Domestic Product (GDP) growth rate of over six percent for the recent years, in the year of 2017-18, Bangladesh attained a GDP of nearly 8% and is set to become the 3rd fastest growing economy in the world [111]. With this continuous economic growth, Bangladesh is working towards a goal of entering into the league of middle-income countries by the year 2021. When this target is attained, the per capita annual income of the country is expected to be more than 2000 USD, and this requires a demand for sustainable energy supply in the country. An increased supply of energy is a must to go hand in hand with the accelerated efforts for the development and growth of a fast-moving economy [27].

There are scopes for improvement in the energy generation sector in Bangladesh and the country is yet to achieve its best in this sector [19]. Based on the GDP growth rate, it is forecasted that the energy usage in Bangladesh is going to be increased significantly over the coming years [112]. By 2030, the peak demand is expected to be 33,700 MW which is distinctively greater than the peak demand in 2010 [113]. The number of industrial companies has notably increased after 1995, causing high energy demand throughout the country. The annual increase of 8% in electricity demand gives an estimated projection of 22,500 MW demand in 2021 where approximately 40% is consumed by the industries [114]. As indicated by recent governmental reports in Bangladesh [115], to sustain the status of lower-middle-income country (for a per capita income of 2000 USD) in 2021, the total use of energy should be 105.5 Mtoe for a population of 171 million. Whereas the projected energy supply in 2021 would be of 88 Mtoe, indicating an apparent lack of energy supply in the existing setup of planning.

The upswing of energy cost and sustainability have impelled industries to find other ways to address energy consumption. It is common knowledge that energy efficiency helps to build a bridge between economics, energy security [7] and environmental objectives [8]. Besides, energy efficiency analysis helps to figure out the possible sectors for energy consumption reduction without hampering energy productivity [117]. Nonetheless, energy efficiency exploration assists the life cycle cost comprehensively in the production process [118]. Unfortunately, many developing countries are still indisposed to benefit the available opportunities offered in the energy efficiency domain due to lack of knowledge and awareness in energy management. Research has shown that the reduction in industrial energy usage can be obtained not only by a greater diffusion of more energy-efficient technological equipment [12], but also through a combination of more efficient energy behaviour and management of the energy resource in the industry [13]. Therefore, it is of utmost importance to take the necessary initiatives in order to implement industrial energy efficiency measures and energy management practices in every possible sector [121].

Several studies have been conducted at multiple demographic locations on industrial energy management practices and how effectively these are carried out. Thollander and Ottosson studied the Swedish energy intensive industries to explore energy management aspects [28]. Cagno et al. studied the barriers and drivers to industrial energy efficiency in the Netherlands [122]. In another study by Trianni et al. barriers to energy efficiencies in foundries at the European context are explored [21]. Rohdin and Thollander investigated the barriers and drivers to energy efficiency in the Swedish foundry industry [116]. Cooremans and Schönenberger focused on energy efficiency in the context of Switzerland [123]. Also, one study studied barriers to energy management in the Swedish pulp and paper industry [124].

Notably, the majority of the previous studies have addressed energy management indistinctly and a comprehensive study is needed in this domain. Moreover, the past and contemporary studies discussed the developed economies mainly. To the best of author's knowledge, yet only a minimal number of studies have addressed energy management and its practices comprehensively in developing countries, with just a few contributions carried out respectively on textile industries [19], SMEs [29], and Ghana's largest industry park [25]. Also, researchers are starting to explore this topic in Bangladesh [27], but literature is far from being mature, offering ample room for further research. Considering the economic growth and industrial advancement in recent days at Bangladesh, this is the high time to look through the energy sector comprehensively and explore the energy domain. Besides, as a developing economy, the learnings can be suited to other emerging economies. In this context, there is a need for in-depth study investigating methods for improving the present energy management practices at the industry offering empirical knowledge in support of academia, industrial decision-makers as well as policy-makers.

This chapter aims at giving a contribution to this research domain by investigating practices for energy management and energy efficiency within the industries of Bangladesh, which are heavily energy reliant. In this study, four key research topics have been explored, which are:

- The probable outcomes of energy management practices in the industries of Bangladesh that are energy-intensive.
- The current states of the industrial processes that are influenced by the actions and technologies related to energy efficiency.
- The availability of a long-term energy strategy at the industries.
- The barriers to implementing energy management practices at the industries.

## 3.2 Literature background

### 3.2.1 Energy Management Characterisation

Energy management is an integral part of industrial production, including the logistics and environmental management system [125]. The cost reduction in operational management is the primary motivation to incorporate energy management into practice at the industries [126]. Energy management can be characterised as the proceedings to work specifically on energy-related issues of industry and considered as one of the key in-house activities for cost-effectiveness and energy efficiency improvement [28]. In this study, energy management is considered as applying to resources, conversion and utilization. It involves measuring, monitoring, logging, analysing, and controlling the energy flows through a system of an industry.

Academics have addressed the definition of industrial energy management that varies from literature to literature, as it consists multiple factors. Schulze et al. [43] have compiled few of the selected definitions of industrial energy management. In one definition, industrial energy management is defined as the accumulation of planned & executed actions for guaranteeing minimum energy input for a predetermined performance. According to them, energy management is also the strategy of meeting energy demand whenever it is necessary. In another attempt, they termed energy management as "*The judicious and effective use of energy*" ensuring maximisation of profits and optimisation of energy efficiency [43].

There are countries which have implemented an energy management system in various industries and got a good result in energy savings. In Denmark, about four hundred companies opted for an energy management system by 2001 and these companies used to consume 60% of the total energy in the whole country. The savings in energy that these companies made ranged from 24% to 62% [27]. Moreover, relevant scientific literature have presented that 40% of energy can be saved with the employment of proper energy management scheme in the industrial sector [127].

In the research domain of energy usage and improving energy efficiency, the researchers focused on the diffusion of cost-effective technologies. However, combined approach of technology [15] and energy management practices have greater impacts to endure the industrial energy efficiency [128].

Nonetheless, there are very little studies (see Table 4) that have actually focused on energy management practices in the industries till now.

Table 4. Selected studies on energy management practices in the industries

| Study | Research Focus | Remark | Reference |
|---|---|---|---|
| Thollander and Ottosson | Foundry, pulp and paper | 40% mills and 25% foundries are successful in energy management. | [28] |
| Brunke et al. | Iron & steel industry | Companies are vigorously affianced in energy management and its practices, nonetheless there are scopes for improvement in prioritisation and awareness within the organisation. | [18] |
| Christoffersen et al. | 304 industrial firms | Among the industries between 3% and 14% practice energy management. | [68] |
| Ates and Durakbasa | Cement, paper & pulp, ceramics, ISI, and textile industries | Degree of energy management solicitation is 22%. | [66] |
| Lawrence et al. | Pulp and paper industry | Specific energy consumption (SEC) is discussed in relation to industrial energy efficiency. Challenges emanate from a lack of information about how SEC is calculated. | [129] |
| Lawrence et al. | Pulp and paper industry | Presence of possible disparity between farm characteristics that are perceived as barriers to energy management. | [130] |
| Backlund et al. | Energy intensive and non-energy intensive industries | 70% of industries have fulltime energy manager, 70% of industries imply to energy strategy | [131] |
| Sivill et al. | Pulp & paper, basic metals, and petro-chemicals industries. | Performance measurement in energy is the third development precedence in energy management. | [132] |
| Lawrence et al. | Pulp & paper | Energy management is not always implemented due to presence of barriers. | [133] |
| Sannö et al. | Volvo CE- a multinational industrial corporation | Introduction of energy management program led to more efficient energy management. The critical elements that characterise efficient energy management were found in the corporate group after the introduction of energy management program. | [134] |
| Andersson and Thollander | Pulp and paper industry | 25% of the mills apply best practice regarding the establishment of energy KPIs. | [135] |

Looking at the literature, it is observed that improved energy management addresses multiple issues. More importantly, the industries are eventually benefitting the benefits stemming from the adoption of energy management practices [126]. Nonetheless, most of the case studies or comprehensive ones are representing the developed economies. There are very few studies that exemplify energy management comprehensively for the developing economies. Therefore, it is significantly necessary to explore the research gap in this area considering the fact of growing energy consumption and economic development of those countries.

### 3.2.2 Taxonomy of drivers and barriers to EE

Since the inception of industrial energy management practices, multiple studies have been conducted to identify and characterise the drivers and barriers to industrial energy efficiency. Furthermore, it is of utmost importance that more efficient and innovative ways for the assessment of barriers and drivers are available so that the policymakers and other concern stakeholders can work together to adopt and implement the required energy-efficient measures (EEMs) [122].

After reviewing a wide range of literature, it is found that the number of recent studies, highlighting the barriers to energy management outweighs the number of works that deal with the recent categorisation of drivers. Several works have studied the barriers to industrial energy management from the theoretical perspectives [17] as well as through different empirical investigations covering SMEs [13], and energy intensive industries [26]. These studies ensure the presence of different types of barriers, and these barriers do create various hindrances in the application of proper EEMs within the enterprises [23]. Furthermore, it is also clear from these studies that firm characteristics like firm size and sector affect the barriers to the implementation of the EEMs [22]. Table 5 comprises different barriers identified by [17] that have been considered in this study.

Table 5. Barriers of energy efficiency based on empirical investigation

| Notation | Barrier | Category |
|---|---|---|
| B 1 | Inadequate support from preeminent administration | Organisation |
| B 2 | Bureaucratic intricacy | Government/Policy |
| B 3 | Insufficient data about energy expenditure allotment | Market/information |
| B 4 | Technical ambiguity | Competence |
| B 5 | Inadequate technical experts | Organisation & competency |
| B 6 | Confined impact on energy management scheme | Behavioural |
| B 7 | Insubstantial attention from concern government | Government |
| B 8 | Lack of staff consciousness | Awareness/ behavioural |
| B 9 | Complex synodical issues | Organisation |
| B 10 | Insufficient data on energy efficiency options | Information |
| B 11 | Imprecise fiscal code | Economic |
| B 12 | Insufficient capital expense | Economic |

| | | |
|---|---|---|
| B 13 | Vulnerability in energy framework (prices, slow rate of return) | Economic |
| B 14 | Poor research and development | Organisation & competency |
| B 15 | Other preferences for capital venture | Economic |
| B 16 | Non visibility of demonstrated technology | Technical |
| B 17 | Inadequate financial incentives | Economic |
| B 18 | Complication in inter-divisional collaboration | Organisation |
| B 19 | Ambiguity about latent costs | Economic |
| B 20 | Time constraint or other obligatory work | Behavioural |
| B 21 | Absence of competent managerial measures | Organisation & competency |

On the contrary, a limited number of resources are available in exploring the drivers which facilitate the energy efficiency practice. Few contributions (e.g. see [25], [108], [136], [137]) have been made in classifying these drivers and their impact in the decision-making practice. In [137], Johansson et al. categorised the driving forces of energy efficiency in four categories: organisational, financial, informational and external. Authors of [22] tabulated some of the recent empirical studies to industrial energy efficiency. As for the taxonomy of the drivers to industrial energy efficiency, the issues are discussed by Thollander et al. focusing Swedish industry [28], Schulze et al. [43], Ates et al. focusing Turkish industry [66], and Thollander & Ottosson featuring paper and pulp industry [138]. Table 6 lists the drivers and their categorisation that are considered in our study.

Table 6. Drivers based on empirical investigation

| Notation | Driver | Category |
|---|---|---|
| D 1 | Energy blueprint | Organisation/ regulatory |
| D 2 | Cost saving due to less end usage of energy | Economic |
| D 3 | Rules and regulations | Policy |
| D 4 | Ambitious individuals | Organisation & competency |
| D 5 | Arrangement for Energy Management | Organisation |
| D 6 | Subsidies for energy efficiency schemes | Economic |
| D 7 | Viable reduction in carbon emissions | Social/awareness/behavioural |
| D 8 | Energy audit endowment | Economic |
| D 9 | Suitable loan for investment with energy management | Economic |
| D 10 | Assurance from preeminent management | Organisation |
| D 11 | Organisational involvement in information and support | Organisation |
| D 12 | Environmental benefits (other than $CO_2$ reduction) | Social/awareness/behavioural |
| D 13 | Owner's requirement | Organisation |
| D 14 | Risk posed by ever increasing price of energy | Market |
| D 15 | Global competition | Market |
| D 16 | Long standing accords with immunity of taxes | Economic |

| | | |
|---|---|---|
| D 17 | Assistance from energy professionals | Technical |
| D 18 | Pressure posed by Non Governments Organisations and clients | Social/awareness/behavioural |
| D 19 | Consultancy provided local jurisdiction | Competency |
| D 20 | System of Green Certification | Social/awareness/behavioural |
| D 21 | Taxes & Tariffs | Economic |
| D 22 | Acquaintances within the energy sector | Market |
| D 23 | External investment | Economic |

Notably, most of the studies focusing drivers and barriers to industrial energy efficiency are conducted in the context of a developed economy. Unfortunately, the same cannot be said for the developing countries, specifically for Bangladesh. In recent time, only two studies featuring steel industry [2], and textile industry [3] have been conducted by Hasan et al. to explore the drivers and barriers towards industrial energy efficiency. Nonetheless, the studies are preliminary and require in-depth exploration. Therefore, a significant research gap exists in the energy management field in Bangladesh. Considering the present industrial growth of the country [139], certainly, there is a high demand to explore the energy management domain comprehensively.

### 3.2.3 Energy Service Companies (ESCOs)

The concept of Energy Services Companies (ESCOs) was developed in the time of 1980s in North America. However, the actions and implementations related to ESCOs began at the close to 1980s and beginning of 1990s [140]. The idea of ESCO started to receive attention due to energy predicament resulting from the oil price hike in the early 1970s [141].

Energy service companies (ESCOs) provide private services for efficient energy management by providing sufficient planning and equipment. The services offered by ESCOs include energy savings, energy efficiency and energy conversion [142]. Besides, the ESCOs also provide multiples types of services that include energy financing, energy and technical consultancy and assistance, equipment installation service along with operation and maintenance. In addition, energy service up-gradation, including monitoring as well as measurement are also incorporated in the features of ESCOs [143]. The ESCO model can be categorised based on their focusing feature (e.g. business or financing). Among the models, the commonly applied business models are “shared savings” and “guaranteed savings” [141]. However, the other models incorporate outsourcing of energy management which are found as significantly prevalent in ESCOs based in the European Union [144].

ESCO industries had insured significant energy savings in many developed and developing countries [142]. Notably, the financing mechanism of ESCOs in the energy improvement sector had successfully delivered in the United States of America, Austria, Japan, South Korea [47] and several European countries [52]. As remittance of ESCO is related to the output achieved by energy savings, unlike conventional firms, countries like Japan and United States of America have carried much research focusing on aspects of ESCO industries [146]. The surge in energy consumption has made the necessity of ESCO momentous, especially in energy-intensive sectors. However, the outcome of [141] suggests that the development of ESCO is dependent on the country's affluence.

However, many developing economies are still reluctant to facilitate of ESCOs. There are few significant studies to find out the hindrances to consult ESCOs in the developing economies. In China, the awareness of energy-saving potential, including inadequate support mechanism, is identified as a substantial barrier [147]. Public awareness, the credibility of ESCOs, and lack of knowledge regarding ESCOs are identified as significant barriers in India [147]. Funding public awareness is found as the foremost barrier in Africa (Egypt, South Africa and Kenya) [140]. In the Philippines, the lack of ESCO business concept is found as a significant barrier. However, in Brazil, energy efficiency marketing is identified as a significant barrier to consult ESCO [140].

It is unblemished by the ephemeral synopsis of the literature presented that energy management is significantly essential to imply energy efficiency in the industries. Very few studies are conducted until now, incorporating the comprehensive inquisition concerning energy management practices in the energy-intensive industrial sector. Based on the circumstances, we have focused on finding the unexplored factors of energy management affecting industrial energy efficiency comprehensively. Hence, in the next section, we present the methods and steps to explore the factors which are significantly affecting energy management in industries.

### 3.3 Methodology

This study was carried out through multiple case study investigation format based on Yin's work [148]. A case study is effective when it addresses the question of 'how' and 'why'. In this format, the researchers do not have any authority on the events [149]. The information was compiled, also thanks to the support of questionnaires in this study, to standardize the sequence questions were asked [150]. In context, the study is conducted in three steps mainly. An intensive literature review & practical cases were studied in the beginning to capitulate on state of the art about energy management and practices in the industries. Later on, the predesigned questionnaire was sent to the stakeholders working at different energy-intensive industries in Bangladesh. A total of thirty-six respondents' feedbacks have been analysed, and data reliability was checked by the Cronbach's alpha test. Finally, the findings that include energy management scenario, drivers and barriers to energy efficiency, energy efficiency potential, and barriers to energy services companies (ESCOs) are presented.

The detailed methods are discussed below and presented in Figure 6.

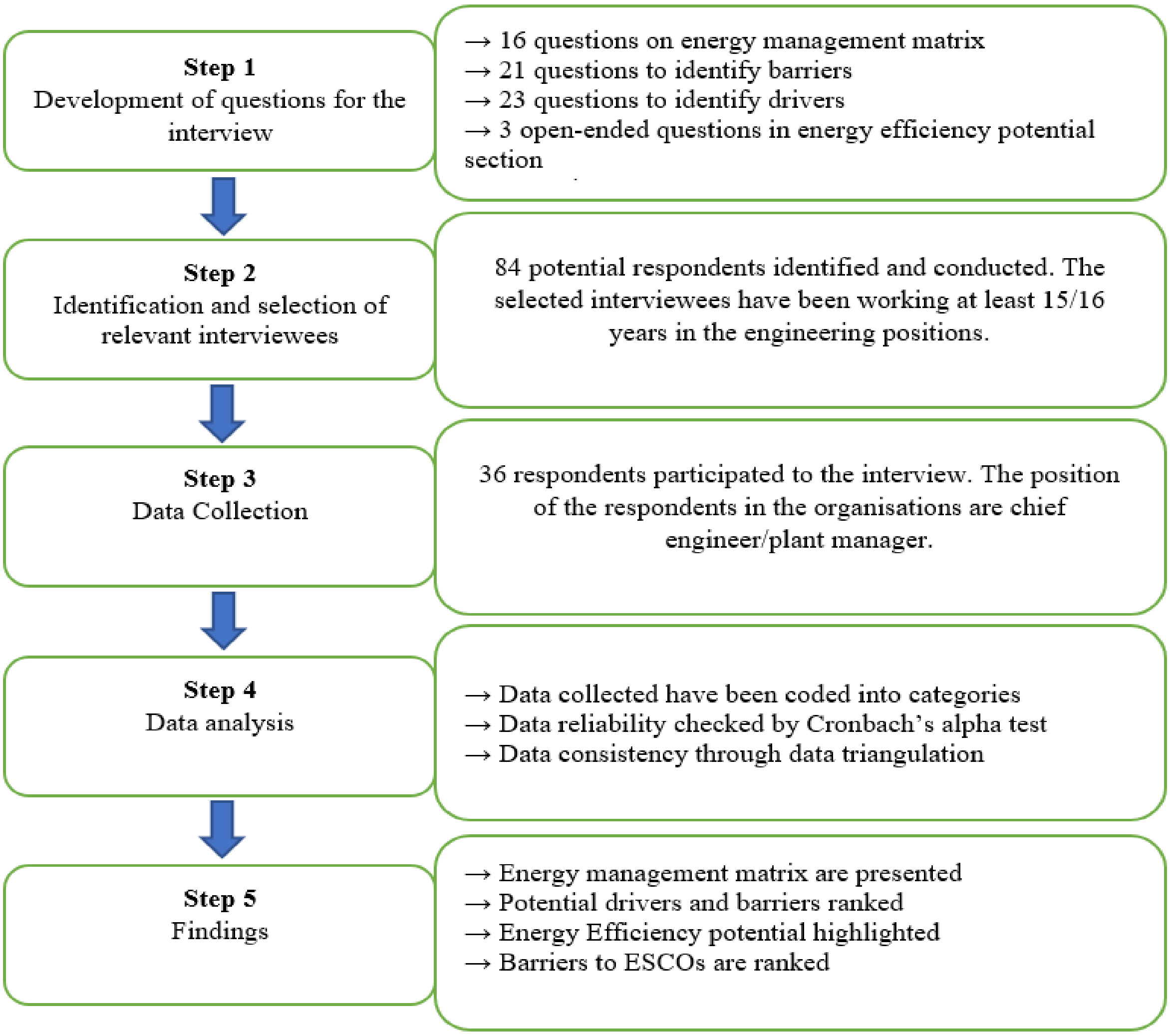


Figure 6. Chronological steps of the methodology of this research

### 3.3.1 Interview

As outlined in the introduction, so far, only a handful of studies have been conducted comprehensively evolving in the theme of energy management at energy-intensive industries to the best of authors' knowledge. Therefore, this study has considered energy management in a comprehensive way incorporating multiple aspects associated with industrial energy management. In this context, we have designed the semi-structured interview with support of a questionnaire divided into several sections to comply with the research gap. The incorporated sections refer to energy management; challenges and motivations for energy efficiency; options for energy efficiency in the industries; energy efficiency potential; and energy service companies (ESCOs). In this study, the questionnaire was designed as a closed format other than the segment named "Energy Efficiency Potential".

In the beginning, the participants were instructed to provide basic details such as revenue, energy end-use, and the number of employees. The significant parts of the questionnaire started with energy management section. The broad categories of possible actions for improved energy efficiency were covered in the energy management section. The classifications that are considered in this segment are the "organisation", "information system", "awareness", "investment", and "policy"- a matrix formulated by the UK's Carbon Trust [83].

The considered categories are linked with energy measurement and ascertained from academic literature for the relevant industries. In the "organisation" section, the questions precisely focused on energy manager and associated issues. The "information system" comprised of energy audits and its frequency related questions. The promotion of energy efficiency and training issues were asked in "awareness" section. The financial issues (e.g. payback, internal rate of return, net present value, and third-party financing) have been discussed at "investment" section. Finally, the policy matters were covered in "policy" segment. Additional success factors are also inclined with the categories devised from relevant literature in this study [70]. The weighting factors considered in this study are devised from relevant literature [18] for various sub-classes while portraying the energy management matrix. The factors for the individual aspect are presented below in Table 7. However, in the "investment" section, weighting factors have been considered for the payback time only to maintain the soundness of the quantification process.

Table 7. The weighted values considered in energy management matrix

| Segment | Issue | Weighted value | Notation |
|---|---|---|---|
| Policy | Inadequate policy/ goals are not properly written | 0.25 | A 1 |
| | Long-term energy strategy (time: 1-3 years) | 0.50 | A 2 |
| | Long-term energy strategy (time: more than 3 years) | 1.00 | A 3 |
| Organisation | no energy manager or part-time energy manager | 0.25 | A 4 |
| | Ad-hoc basis energy manager | 0.50 | A 5 |
| | Dedicated full-time energy manager | 1.00 | A 6 |
| Information System | Energy audits are conducted | 1.00 | A 7 |
| | Frequency: Daily | 1.00 | A 8 |
| | Frequency: Monthly - Weekly | 0.50 | A 9 |
| | Frequency: Annually - Quarterly | 0.25 | A 10 |
| | Type of energy: Steam and hot-water | 0.25 | A 11 |
| | Type of energy: Fuel | 0.25 | A 12 |
| | Type of energy: Electricity | 0.25 | A 13 |
| | Allocation of Energy: Sub-metering | 1 | A 14 |
| | Allocation of Energy: Per tonne | 0.25 | A 15 |
| Awareness | Absence of promotional activities including training on energy efficiency | 0.25 | A 16 |
| | Some ad-hoc staff awareness training; newsletters/posters | 0.50 | A 17 |

| | | | |
|---|---|---|---|
| | Regular activities on energy efficiency and its marketing value | 1.00 | A 18 |
| Investment | Payback time for less than 1 year | 0.25 | A 19 |
| | Payback time between 1 and 2 years | 0.50 | A 20 |
| | Payback time between 2 and 3 years | 0.75 | A 21 |
| | Payback time for more than 3 years | 1.00 | A 22 |

The next section covered the queries focusing barriers to industrial energy efficiency. The questions featured factors like technical, financial, organisational, and policy restraints. However, this section also covered the future challenges posed by the competitors. The following section inquired about the drivers to energy efficiency. The questions representing both the barriers and drivers to energy efficiency are presented in Table 5 and Table 6. The inclusion of the questions followed similar well-established approaches in research conducted in other sectors (e.g., studies focused on steel industries [2], textile industries [3], and cement industries [110]).

The possibilities and opportunities for practicing energy efficiency were covered in the fourth section. In this part, specific questions featuring energy reduction were asked to the participants. Nonetheless, the concluding phase of the questionnaire focused on energy service companies (ESCOs). The potential barriers to ESCOs were asked in this section.

### 3.3.2 Stakeholders for the investigation

The questionnaire was sent to personnel who have a great deal of experience in their respective fields, such as plant managers or chief operating engineers. Notably, all the respondents considered in this study are working in the industrial sector for more than 15/16 years. As they are the key people in running the operations, their insights bring significant value to the study. The responses were considered through arithmetic means only, by a numbered Likert scale. The criterion for selecting the energy-intensive industries was energy cost allocation. The companies having energy cost more than 8% of total revenue are considered as energy-intensive industries in this study. The list of industries that fulfills the criterion of this study was collected from the Bangladesh Export Processing Zone Authority.

### 3.3.4 Data collection, analysis and findings

Thirty-six (36) industries agreed to take part in this study out of eighty-four (84) companies. The response rate is satisfactory compared to other studies conducted at different scenarios and context. The reason behind the high response rate is an instruction from the higher authority and willingness to participate in energy management studies. In addition, the Sustainable and Renewable Energy Development Authority (SREDA), one of the controlling organisations of energy issues in Bangladesh, instructed the industries to participate in different energy studies [151]. Similar studies were conducted for textile industries [19] and non-energy intensive manufacturing industries of Bangladesh [29]. The response rate for textile industries was 40%, and non-energy intensive industries were 23%. The participants were instructed to rate the perceived drivers and hurdles in the scale of *"0 (Not important)"* to *"1 (Extremely important)"*. The feedback of the respondents was cross-checked later on via telephonic conversation. For the internal consistency of the study, Cronbach's Alpha parameter was used. Any value of alpha higher than 0.75 were considered as reliable [61].

Table 8. Investigation approach at a glance

| Topic | Remark |
|---|---|
| No. of industries questionnaire was sent | 84 |
| Total respondents | 36 |
| Response rate | 43% |
| Respondent's designation | Plant manager/ Chief engineer |
| No. of questions asked | 64 |
| Outsourcing option | No |

The influential issues on energy management practices are ranked and presented in the results and discussion section. The arithmetic means are considered only on the responses. Nonetheless, the discrepancies in perceptions are not taken into consideration in our study. In addition, the statistical frequency distribution has been incorporated to highlight the data analysis. In the statistical domain, the frequency table is one of the basic tools for presenting descriptive statistics and commonly applied into the dissemination of data [154]. The data representation in the frequency table or graphical visualisation is useful to analyse categorical data as well as screening data for data entry errors [155]. Analysis by correlation is also conducted to further explore the relation among the aspects of energy management, drivers and barriers to energy management, and barriers to energy services companies.

A similar data analysis approach had been widely adopted by previous literature in the industrial energy efficiency and energy management domains. Hasanbeigi et al. focused on the Thai industry [156] and presented the barriers to industrial energy efficiency incorporating basic statistical analysis. In another study, Rohdin et al. investigated the barriers and drivers within the Swedish foundry industry [116] with a similar approach. Likewise, Trianni et al. explored barriers to industrial energy efficiency in European foundries [21]. Johansson studied the Swedish steel industry [14], whereas Backman focused on the SMEs [157].

### 3.4 Energy management practices

There are standards and guidebooks in the industry and academia addressing the energy management. However, majority of them are covering only the technical and buildings perspectives. The ISO 50001 is a significant standard, though, it covers the energy management issues in a generic way. Comprehensive guidebooks on industrial energy management featuring technical perspectives as well as policy, managerial, and other issues are still lacking.

In this study, Energy Management Matrix by Carbon Trust is applied to maintain the consistency with current energy management standards. The energy management matrix provides significant insights about any organisation's current position with respect to energy management [18]. The matrix was complemented with notable success factors towards energy management practices as like energy strategy, top management support, sub-metering issues and so forth. The companies were assigned points for each considered factor (e.g. policy, organisation, information systems, awareness, and investment). By doing so, we receive more granular understanding about actual situation of energy management in the energy intensive industries of Bangladesh.

Here, we have presented the total sample results in Section 4.1, also analysing the frequencies of responses. In addition, we have performed a preliminary analysis of the correlations presented in Section 4.2 to further explore the energy management and associated aspects.

#### 3.4.1 Analysis of energy management matrix by average score and frequency of responses

Figure 7 presents the energy management matrix along with frequency of responses and average value. By analysing the result, we can observe several interesting findings. Firstly, energy audits (average of 0.78) represent the most implemented practice, followed by energy monitoring (frequency daily to annually/quarterly), all following under the category of "information systems". However, the audits are conducted by in-house stakeholders in most cases. Notably, to overcome the energy efficiency gap, governmental industrial energy audit programs subsidising the enterprises are the most common policy [158]. We find in this study that, a gap still exists in this sector at Bangladesh between the governmental initiatives and industrial energy audits. In addition, a comprehensive energy audit on a detailed level is to be preferred in the industries to bring additional benefits as well as to encourage the industries to work continuously with energy efficiency by incorporating it into the organisation's management. The energy service companies (ESCOs) can contribute significantly into the energy audit program. We find that most of the companies are unaware about energy service companies and their offerings. Therefore, we recommend to incorporate the ESCOs at the industries to best leverage not only to the energy audits but also energy management in a broader umbrella.

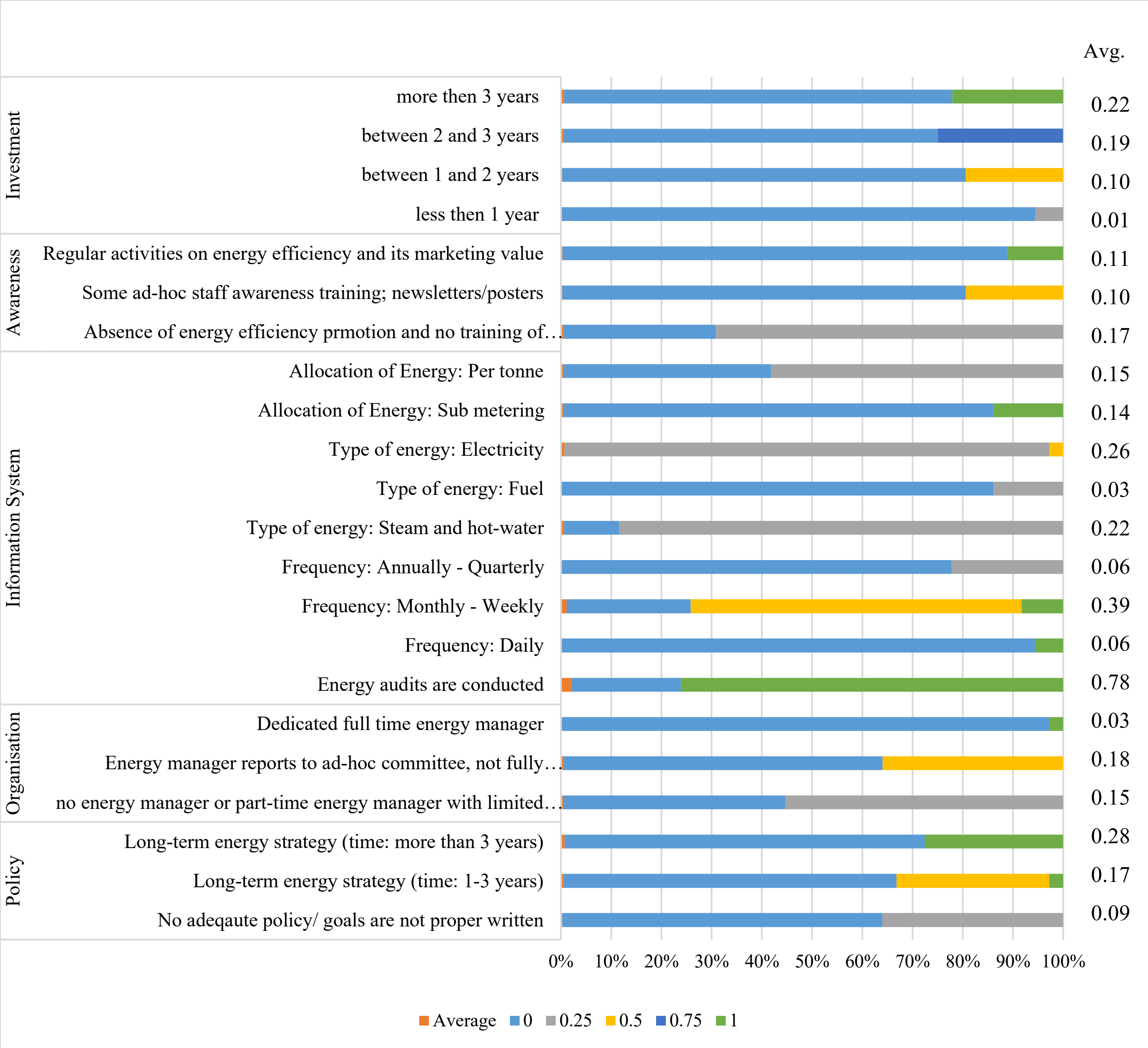


Figure 7. Energy management matrix, with frequency of responses and average for the whole sample

Secondly, there are only a few practices with values higher or closer to 0.5, indicating that the vast majority of the companies barely implement the energy management practices proposed. In the industrial energy efficiency domain, two significant studies conducted by Backlund et al. [15], and Palm & Thollander [159], have distinctly stated that it is only possible to maximise the energy efficiency with the combined approach of energy efficient technical measures along with energy management & its practices, given that the sole diffusion of energy efficient technologies is not sufficient to harness the full energy efficiency features. Considering the recent industrial development [139], it seems urgent for a developing economy like Bangladesh to focus on industrial energy management comprehensively in order to ensure efficiency and sustainability at the industries.

Thirdly, we find that almost entire of the sampled industries do not integrate full time energy manager into the organisational structure (only 1 out of 36 does). The energy manager should be considered as a dedicated post in the organisational structure to be responsible for monitoring and analysing energy as well as resource consumption so as to develop, get approved and implement consistent energy efficiency projects. However, today's energy manager is a multifaceted character with modernised knowledge and expertise linking multiple fields beyond energy; including technology, environment, people, finance, personal & enterprise communication, and information technologies [160]. The integration of energy manager into the organisational structure with higher power could significantly contribute towards increasing energy efficiency and sustainability in a company. In this regard, the absence of energy manager is identified as one of the major barriers to comply energy efficiency measures in industries [161]. Moreover, a comprehensive energy management program incorporating energy manager along with other energy management practices is capable to bring a significant return on investment as well as improvement in terms of cost competitiveness, as earlier research shows [162]. Therefore, the inclusion of an energy manager becomes even more important for the energy intensive industries where a significant portion of overhead costs are attributed to energy cost.

Currently, in the companies that took part in the study, either electrical or mechanical engineers are responsible for managing the energy issues (not comprehensively) in their plants. Though the concept of energy manager in the industries is relatively new in many countries, the necessity of an efficient and dedicated person to deal with energy issues have always been realised. In this regard, it thus seems important for concerned stakeholders (e.g. owners, policy-makers) to consider integrating dedicated energy managers in the industries.

Fourthly, we can see that only a limited number of companies (10 out of 36) have implemented a long term energy strategy with an investment perspective longer than 3 years. This result is particularly critical as it may jeopardise the success of many valuable initiatives for improving energy efficiency, suggesting that, at least from the investigated sample in a developing economy, companies are far from considering energy efficiency investments with a strategic perspective, as suggested by Cooremans [163]. Furthermore, we have analysed the frequency of responses by individual category (e.g. awareness, organisation, investment, policy, and information system), as presented and discussed below.

***Awareness***

In the studied organisations, the segment that has very low value in frequency of responses and requires utmost improvement is "awareness" related to energy management. The concerned stakeholders at all levels are needed to be taught about energy management practices, including the capacity of intensifying the production. By looking at Figure 7, it can be seen that promotional activities are the most visible gap that needs to be addressed immediately. However, the regular activities on energy efficiency & its associated value also demand the attention to be given adequately.

***Organisation***

The organisations need to consider energy efficiency conjecture, and thus the integration of dedicated energy engineer or energy manager into the organisational hierarchy is much crucial. Looking at Figure 7, it can be observed that the industries suffer most due to lack of full-time energy manager.

Considering the present industrial growth in Bangladesh, maintaining some standardisations specially the ISO 50001 seems one of the best ways to deal with energy management issues. Looking at the result, it can be seen that a significant gap exists in the energy management field comprising to "awareness" and "organisation". The ISO 50001 becomes even more important when we tend to focus energy management from organisational perspectives. The ISO 50001 is expected to enable all the features and tools for the industries by which the local industries can examine their processes and systems related to energy performance [69], efficiency and intensity [70]. In addition, by executing the standard ISO 50001, the organisations will have the options to appliance a holistic energy management system that includes energy targets, objectives and policy [166]. The features of the standard ISO 50001 can also be modified based on the organisation's requirement [167].

***Investment***

In the "investment" category of energy management matrix, it is found that 26 industries use payback time to calculate the profit, showing an overall lack of knowledge over the main techniques for conducting a proper investment analysis, which is however diffused also in other developed economies as previous research notes [168]. In fact, only seven industries calculate the net present value (NPV) as well as the internal rate of return (IRR). In doing this, only eight industries are found that consider investments with payback times longer than three years. Furthermore, it is found that energy-intensive industries are mostly short-term profit-oriented and focus on other prioritised financial investments. Therefore, the share of financial investment at large industries related to energy management needs to be increased.

***Policy***

The policy has a great significance when it comes to the issue of industrial energy efficiency measures implementation. By looking at Figure 7, it is observed that there remains a certain gap in the policy framework in the industries of Bangladesh. Most of the industries suffer due to long term energy strategy. Therefore, standardised policy framework should be established in a long term basis from the government as well as other concerned stakeholders, to implement industrial energy management system properly.

Nonetheless, the inception of policies for energy management, efficiency and auditing in Bangladesh was in 2015, based on previous energy policies. The National Energy Policy of 2004, was the first precursor in this context, where its preceding policies were concerned with deficiency of systematic development in the generation, distribution and transmission of energy, as well as data collection, utilisation and research of potential energy sources. Furthermore, the Sixth National Five-Year Plan (2011-2015) paid more attention to extenuating the mismatch between the supply and demand of electrical energy by importing energy from neighboring countries and Public-Private Partnership (PPP). This particular policy implicitly promoted energy efficiency through several key measures to support energy-efficient usage, such as fuel diversification, scheduling of demand, price revision, lowered taxes for importing power plant equipment, distribution of energy-efficient CFL bulbs, and so on, and made its place in the Seventh Five-Year Plan (2016-2020) of Bangladesh, as well. USAID (an American organisation) completed a country-wide program in 2012, which was titled "Catalysing the Energy Efficiency in Bangladesh" targeting the increase of energy efficiency in the industries [169].

However, a comprehensive approach is still lacking to address the standardized policy framework that incorporates specific focus on industrial energy management. The existing policies do not have clear guidelines about top management integration with energy efficiency measures, presence of energy manager, monetary fines for not complying, tiering of energy auditors, and more importantly awareness program among the employees about energy efficiency. As a result, the task of implementation becomes more challenging due to the weakened ability of enforcement [170]. According to a study conducted in Italy and the United Kingdom, even after having an effective technical policy, governments often introduce several neoclassical approaches that do not target the energy efficiency plan [171].

***Information System***

The provisions of energy cost through sub-metering and energy audit are essential to achieve energy management profoundly. Our findings show that 21 industries among 36 earmark their energy in terms of a tonne. However, the number of industries use sub-metering are 5. Interestingly, none of the industries allocates the energy cost in terms of the square meter or employee basis. Notably, all the industries rely on electricity for activities. Besides, there are five industries that consider natural gas as fuel. Notably, 28 industries had gone through the energy audit (not in a comprehensive manner).

### 3.4.2 Correlation analysis of Energy Management

A preliminary analysis of correlations has been performed to highlight some possible relationships between practices within the Energy Management Matrix. Considering the exploratory nature of the study and the limited number of investigated companies, we have limited our following comments exclusively to the strongest correlations, highlighted in Table 9 (red, “very strong” >=0.8; yellow, “strong” >=0.7). From this first analysis, we can see that the correlation is overall low, therefore with interviewees not seeming to link a number of possible relationships between practices in the EMM. This may mean that companies are lacking to see at the proposed practices with a (either positive or negative) synergic approach, thus with the implementation of some practices fostering (or hindering) the adoption of others. Again, this result seems to show that companies are not taking a holistic view over energy management as an integrated approach, rather implementing practices in a scattered way.

Further, we can note that some correlations have been highlighted within the same categories. In particular:

- No energy manager or part-time energy manager with limited authority and energy manager reports to ad-hoc committee, not fully responsible for energy consumption : (0.84)
- Energy Monitoring (Frequency: Monthly - Weekly) and Energy Monitoring (Frequency: Annually - Quarterly): (0.81)
- Absence of energy efficiency promotion and no training of officials and some ad-hoc staff awareness training; newsletters/posters: (0.74)

In particular, we can observe that the lack or limited authority of an energy manager (A 4) represents a potential issue, where the energy manager also reports to the ad-hoc committee (A 5). This issue particularly has impact on barriers to energy efficiency (such as the organisational one on long decision chain, or the low rank of energy efficiency in the organisational chart), as discussed further. Furthermore, we have noted that another two practices within the information systems category present higher correlation coefficients, such as Energy Monitoring (Frequency: Monthly – Weekly, A9) and Energy Monitoring (Frequency: Annually – Quarterly, A10). Such finding may reflect the capability of some companies to scale up to higher frequency for accounting once started to implement the energy monitoring practices. Therefore, it seems to represent an interesting finding related to the lower inertia of more deeply implementing a very important set of energy management practices such as energy monitoring, which is essential for increased knowledge and decision-making. Additionally, we have observed a strong correlation between absence of promotional activities including training on energy efficiency (A 16) and some ad-hoc staff awareness including training, newsletters/ posters (A 17). The correlation seems to reflect how the staff awareness and trainings on energy efficiency measures are affected by absence of promotional activities including training on energy efficiency.

Table 9. Total sample analysis of correlations. Significant values are represented in bold

| | | Policy | | | Organisation | | | Information System | | | | | | | | | Awareness | | | Investment | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A 1 | A 2 | A 3 | A 4 | A 5 | A 6 | A 7 | A 8 | A 9 | A 10 | A 11 | A 12 | A 13 | A 14 | A 15 | A 16 | A 17 | A 18 | A 19 | A 20 | A 21 | A 22 |
| Policy | A 1 | 1.00 | 0.51 | 0.47 | 0.21 | 0.20 | 0.22 | 0.15 | 0.32 | 0.02 | 0.12 | 0.27 | 0.13 | 0.13 | 0.13 | 0.07 | 0.25 | 0.07 | 0.29 | 0.07 | 0.08 | 0.03 | 0.26 |
| | A 2 | | 1.00 | 0.42 | 0.44 | 0.36 | 0.11 | 0.11 | 0.16 | 0.02 | 0.14 | 0.07 | 0.12 | 0.11 | 0.03 | 0.04 | 0.33 | 0.20 | 0.24 | 0.06 | 0.19 | 0.03 | 0.11 |
| | A 3 | | | 1.00 | 0.18 | 0.08 | 0.10 | 0.03 | 0.15 | 0.15 | 0.12 | 0.37 | 0.29 | 0.27 | 0.11 | 0.02 | 0.13 | 0.17 | 0.02 | 0.15 | 0.15 | 0.07 | 0.27 |
| Organisation | A 4 | | | | 1.00 | **0.84** | 0.19 | 0.19 | 0.22 | 0.24 | 0.33 | 0.32 | 0.13 | 0.15 | 0.36 | 0.30 | 0.11 | 0.02 | 0.14 | 0.03 | 0.16 | 0.26 | 0.07 |
| | A 5 | | | | | 1.00 | 0.13 | 0.29 | 0.18 | 0.30 | 0.29 | 0.27 | 0.03 | 0.13 | 0.30 | 0.28 | 0.12 | 0.08 | 0.08 | 0.07 | 0.08 | 0.23 | 0.26 |
| | A 6 | | | | | | 1.00 | 0.09 | 0.04 | 0.25 | 0.32 | 0.06 | 0.07 | 0.03 | 0.07 | 0.20 | 0.25 | 0.34 | 0.06 | 0.04 | 0.08 | 0.29 | 0.09 |
| Information System | A 7 | | | | | | | 1.00 | 0.13 | 0.16 | 0.13 | 0.02 | 0.02 | 0.09 | 0.02 | 0.18 | 0.37 | 0.09 | 0.66 | 0.13 | 0.08 | 0.15 | 0.04 |
| | A 8 | | | | | | | | 1.00 | 0.15 | 0.13 | 0.09 | 0.25 | 0.04 | 0.10 | 0.29 | 0.16 | 0.12 | 0.09 | 0.06 | 0.12 | 0.14 | 0.13 |
| | A 9 | | | | | | | | | 1.00 | **0.81** | 0.05 | 0.02 | 0.05 | 0.27 | 0.05 | 0.09 | 0.11 | 0.27 | 0.15 | 0.40 | 0.41 | 0.16 |
| | A 10 | | | | | | | | | | 1.00 | 0.02 | 0.02 | 0.09 | 0.02 | 0.09 | 0.06 | 0.08 | 0.19 | 0.16 | 0.26 | 0.46 | 0.13 |
| | A 11 | | | | | | | | | | | 1.00 | 0.14 | 0.48 | 0.62 | 0.24 | 0.34 | 0.27 | 0.16 | 0.09 | 0.05 | 0.20 | 0.45 |
| | A 12 | | | | | | | | | | | | 1.00 | 0.07 | 0.16 | 0.01 | 0.09 | 0.01 | 0.14 | 0.10 | 0.20 | 0.14 | 0.17 |
| | A 13 | | | | | | | | | | | | | 1.00 | 0.42 | 0.20 | 0.25 | 0.34 | 0.06 | 0.04 | 0.08 | 0.10 | 0.32 |
| | A 14 | | | | | | | | | | | | | | 1.00 | 0.48 | 0.26 | 0.21 | 0.11 | 0.10 | 0.41 | 0.23 | 0.17 |
| | A 15 | | | | | | | | | | | | | | | 1.00 | 0.30 | 0.44 | 0.12 | 0.29 | 0.15 | 0.10 | 0.05 |
| Awareness | A 16 | | | | | | | | | | | | | | | | 1.00 | **0.74** | 0.53 | 0.16 | 0.02 | 0.03 | 0.23 |
| | A 17 | | | | | | | | | | | | | | | | | 1.00 | 0.17 | 0.12 | 0.06 | 0.04 | 0.24 |
| | A 18 | | | | | | | | | | | | | | | | | | 1.00 | 0.09 | 0.05 | 0.00 | 0.02 |
| Investment | A 19 | | | | | | | | | | | | | | | | | | | 1.00 | 0.12 | 0.14 | 0.13 |
| | A 20 | | | | | | | | | | | | | | | | | | | | 1.00 | 0.28 | 0.26 |
| | A 21 | | | | | | | | | | | | | | | | | | | | | 1.00 | 0.31 |
| | A 22 | | | | | | | | | | | | | | | | | | | | | | 1.00 |

### 3.5. Barriers to energy efficiency

### 3.5.1 Analysis of barriers by average score and frequency of responses

Figure 8 reports perceived barriers to energy management initiatives, including average values and frequencies of responses. The outcomes demonstrate "Inadequate support from preeminent administration" and "Bureaucratic intricacy" as significant hindrances to energy efficiency in energy-intensive industries of Bangladesh. The other noteworthy distinguished barriers were "Insufficient data about energy expenditure allotment" and "Technical ambiguity".

The high ranked barriers that have emerged, namely "Inadequate support from preeminent administration (average score: 0.90)" and "Bureaucratic intricacy (average score: 0.83)" point out the administrative hurdles affecting the enterprises. In both cases, more than 30 out of 36 interviewees deemed those barriers at least important (34/36 and 32/36, respectively), and none of the participants marked this issue as "not important". Indeed, this expresses the significance of administration support to adopt energy efficiency measures in the industries. This is interesting as well as an unique finding considering the fact that, being a developing economy, financial constraints are not deemed as major barriers towards energy management in the energy intensive industries.

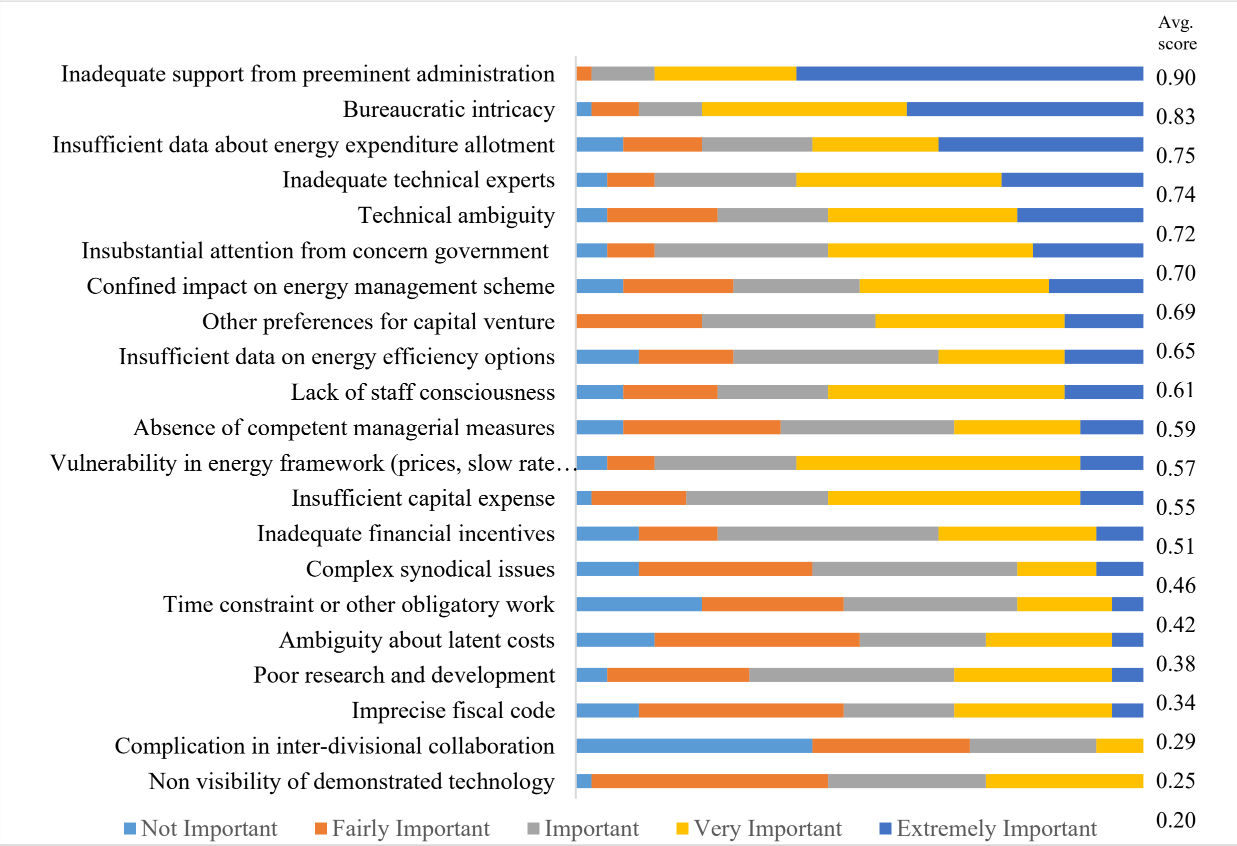


Figure 8. Perceived barriers –frequency of responses

Relating our findings to previous literature, we can note that here the bureaucratic issues are perceived with much greater relevance compared to other barriers such as financial ones and other priority of several distinct barriers for improved energy efficiency are observed, substantially differing from earlier studies, although conducted in different economies and industrial contexts. In fact, in the present study, inadequate financial incentives present an average score of 0.34, with none of the respondents pointing them as extremely important. Rather, previous studies conducted in Sweden indicated that the "Access limitation of capital" and "Insufficient budget", as well as "Technological risks", as the significant hindrances for them [116]. When looking at Swedish Iron and Steel industries [18], authors show that the technical risks and limited access to capital are the most substantial obstacles. A similar study (not limited to energy-intensive industries only) was conducted in Ghana, showing the most prevalent barriers being financial; such as "Access limitation of capital", "Insufficient budget" and "Other priorities for investment" were the high ranked barriers [25].

Another study conducted in Turkey identified “Financial supports” as a significant barrier towards energy management and efficiency programs [66]. Also in comparison with previous research within textile industries [19], “Inadequate capital expenditure” was identified as the most significant barrier, which is indeed different from our present findings. In the United Kingdom, study identified other primacies for capital investment, inadequate time, inappropriate technology as the reasons for not implementing industrial energy efficiency measures [172]. Similar type of financial aspects that include poor return rate, longer payback time have been identified for the Australian firms [109]. In [23], the authors classified the barriers into several categories (e.g., behavioural, organisation technological, economic) and investigated the influence of the drivers to the barriers in a comprehensive manner, finding the economic barriers as the most influential. Another previous study [122] conducted for the Dutch industries shows that the enterprises are in agreement about the most important barriers, as well as about underlying mechanisms. Interestingly, study conducted in India, another emerging economy, identified financial barrier towards industrial energy efficiency measures [173].

Furthermore, our interviewees highlighted the lack of adequate data about energy expenditure allotment as major barrier (average score: 0.76). Again, the relevance of this barrier does not find major confirmation in earlier literature in developing economies, whilst discussed in other developed European countries focusing SMEs [11], and foundries [12]. However, the present findings confirm earlier results from technical ambiguity observed within steel industries in Bangladesh [27] again perceived as quite relevant (average score: 0.74). But, we can observe many dissimilarity in the findings between steel industries and present study, where the technical ambiguity, together with uncertainty over energy prices were identified as the imperative barriers to energy efficiency measures, whilst here we have observed bureaucratic issues.

Additionally, our investigation revealed that staff awareness presents a medium relevance, with an average score of 0.65 and 23/36 enterprises deeming it as at least important. Our findings here differ from earlier literature conducted in Malaysian manufacturing firms pointing out “Commitment from higher management”, “Energy awareness” and “Knowledge gap” as the prominent barriers. However, this study also emphasized concern for reducing $CO_2$ among the stakeholders [175]. In another study focusing on cement industries [110], “Lack of staff consciousness” is identified as the most imperative barrier towards energy efficiency measures. The discrepancy of our findings compared to earlier literature could be attributed to a number of reasons, including working environment, production nature, and other contextual factors. We acknowledge that the moderating effect of some contextual variables could represent a valuable opportunity for future research.

Notably to observe that the barriers of low ranked (lack of time and absence of competent managerial measures, with average scores of 0.20 and 0.16, respectively) are also referring to organisational internal framework at present relating energy management and its practices.

In a nutshell, we can observe that sampled companies tend to blame external stakeholders for not receiving adequate support, rather than highlighting major internal hurdles preventing them to more systematically implement energy management and energy efficiency initiatives. In this case, we can find confirmation in earlier literature. However, here we are limiting our analysis to the perceived barriers, not discussing in depth possible misalignments with real barriers, as previous research pointed out at [168].

### 3.5.2 Correlation analysis of barriers

By looking at the major correlations Table 10 (red, “very strong” >=0.8; yellow, “strong” >=0.7), we find several interesting very strong correlations, in particular:

- Insufficient data on energy expenditure allotment (B 3) and confined impact on energy management scheme (B 6): (0.83)
- Insufficient data about energy expenditure allotment (B 3) and technical ambiguity (B 4): (0.85)
- Technical ambiguity (B 4) and inadequate technical experts (B 5): (0.81)
- Technical ambiguity (B 4) and insubstantial attention from concern government (B 7): (0.80)
- Technical ambiguity (B 4) and confined impact on energy management scheme (B 6): (0.82)
- Inadequate technical experts (B 5) and confined impact on energy management scheme (B 6): (0.91)
- Inadequate technical experts (B 5) and Insubstantial attention from government (B 7): (0.95)
- Inadequate technical experts (B 5) and lack of staff consciousness (B 8): (0.83)

- Confined impact on energy management scheme (B 6) and Insubstantial attention from government (B 7): (0.96)
- Insubstantial attention from government (B 7) and lack of staff consciousness (B 8): (0.91)
- Insubstantial attention from government (B 7) and complex synodical issues (B 9): (0.88)
- Lack of staff consciousness (B 8) and complex synodical issues (B 9): (0.95)
- Confined impact on energy management scheme (B 6) and lack of staff consciousness (B 8): (0.82)
- Confined impact on energy management scheme (B 6) and complex synodical issues (B 9): (0.82)
- Non visibility of demonstrated technology (B 16) and inadequate financial incentives (B 17): (0.84)

Acknowledging the limited size of the sample and the exploratory nature of the investigation, we opt to comment over the major trends in the correlations, suggesting that further research with enlarged sample size could deepen such preliminary considerations. By observing the correlation, we can see that insufficient data on energy expenditure allotment (B3) seems to present a strong relationship with impact of energy management scheme (B6) and technical ambiguity (B4). This seems to indicate that the lack of data on energy expenditure is effectively connected to poor decision-making into companies, with limited understanding on the impact that proper energy management would have, also related to greater difficulties in terms of perceived compatibility of technologies. One possible reason for insufficient data on energy expenditure might be the transparency issue on expenditure from management towards employee.

To corroborate out considerations over poor decision-making in industry, our exploratory investigation shows that technical ambiguity (B4) presents a strong correlation also with inadequate technical experts (B5), lack of attention from government (B7). Here, one significant finding is that the technical uncertainty is perceived greater when technical expertise is lacking. These findings find confirmation in earlier literature focused on developed countries [174] also relating such difficulties with deficit of energy expertise in the industries. Nonetheless, we observe strong impact for inadequate technical experts with lack of attention from government as well as lack of staff consciousness on energy management. Indeed, the government is pointed as a significant stakeholder to build local expertise and adopt technical modifications comprehensively in society, however not yet acknowledging the role of other potential stakeholders in offering valuable vocational training and expertise over energy management, as observed in other industrial contexts [22]. The impact of government concern becomes even more important when it comes to imply the rules and regulation into organisational process, which also refer to our findings presented in Table 10. Interestingly, lack of attention from government (B7) seems also connected to lack of staff consciousness (B8). This correlation again indicates the importance of governmental attention to make the staff aware on energy management issues.

However, the found correlation between confined impacts on energy management scheme (B6) with lack of staff consciousness (B8) points out to the organisational internal context. In contrast with studies conducted in the European foundries [21], lack of influence of energy manager and low priority given to energy management is also observed as possible relationship.

Table 10. Total sample analysis of correlations. Significant values are represented in bold

| | B 1 | B 2 | B 3 | B 4 | B 5 | B 6 | B 7 | B 8 | B 9 | B 10 | B 11 | B 12 | B 13 | B 14 | B 15 | B 16 | B 17 | B 18 | B 19 | B 20 | B 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B 1 | 1.00 | 0.70 | 0.32 | 0.23 | 0.32 | 0.29 | 0.29 | 0.28 | 0.31 | 0.25 | 0.19 | 0.21 | 0.12 | 0.09 | 0.18 | 0.09 | 0.00 | 0.02 | 0.17 | 0.21 | 0.23 |
| B 2 | | 1.00 | 0.57 | 0.47 | 0.48 | 0.52 | 0.45 | 0.38 | 0.38 | 0.33 | 0.31 | 0.28 | 0.26 | 0.14 | 0.09 | 0.06 | 0.09 | 0.09 | 0.04 | 0.19 | 0.16 |
| B 3 | | | 1.00 | 0.85 | 0.75 | 0.83 | 0.72 | 0.59 | 0.50 | 0.46 | 0.49 | 0.44 | 0.41 | 0.25 | 0.20 | 0.21 | 0.05 | 0.17 | 0.25 | 0.35 | 0.35 |
| B 4 | | | | 1.00 | 0.81 | 0.82 | 0.80 | 0.70 | 0.63 | 0.59 | 0.57 | 0.58 | 0.59 | 0.44 | 0.41 | 0.34 | 0.20 | 0.31 | 0.24 | 0.33 | 0.30 |
| B 5 | | | | | 1.00 | 0.91 | 0.95 | 0.83 | 0.75 | 0.69 | 0.61 | 0.65 | 0.61 | 0.44 | 0.37 | 0.20 | 0.01 | 0.13 | 0.24 | 0.28 | 0.30 |
| B 6 | | | | | | 1.00 | 0.96 | 0.82 | 0.82 | 0.74 | 0.56 | 0.43 | 0.32 | 0.20 | 0.22 | 0.12 | 0.14 | 0.31 | 0.26 | 0.25 | 0.12 |
| B 7 | | | | | | | 1.00 | 0.91 | 0.88 | 0.82 | 0.66 | 0.48 | 0.44 | 0.32 | 0.34 | 0.18 | 0.22 | 0.41 | 0.25 | 0.25 | 0.13 |
| B 8 | | | | | | | | 1.00 | 0.95 | 0.86 | 0.60 | 0.37 | 0.40 | 0.33 | 0.39 | 0.17 | 0.22 | 0.38 | 0.18 | 0.31 | 0.09 |
| B 9 | | | | | | | | | 1.00 | 0.86 | 0.63 | 0.44 | 0.38 | 0.28 | 0.33 | 0.15 | 0.19 | 0.31 | 0.15 | 0.25 | 0.19 |
| B 10 | | | | | | | | | | 1.00 | 0.78 | 0.47 | 0.50 | 0.37 | 0.39 | 0.19 | 0.23 | 0.33 | 0.21 | 0.28 | 0.10 |
| B 11 | | | | | | | | | | | 1.00 | 0.78 | 0.78 | 0.66 | 0.59 | 0.34 | 0.35 | 0.45 | 0.12 | 0.11 | 0.13 |
| B 12 | | | | | | | | | | | | 1.00 | 0.84 | 0.73 | 0.65 | 0.44 | 0.36 | 0.48 | 0.10 | 0.06 | 0.19 |
| B 13 | | | | | | | | | | | | | 1.00 | 0.88 | 0.76 | 0.48 | 0.46 | 0.59 | 0.14 | 0.02 | 0.04 |
| B 14 | | | | | | | | | | | | | | 1.00 | 0.83 | 0.55 | 0.49 | 0.55 | 0.04 | 0.00 | 0.21 |
| B 15 | | | | | | | | | | | | | | | 1.00 | 0.64 | 0.56 | 0.57 | 0.07 | 0.01 | 0.24 |
| B 16 | | | | | | | | | | | | | | | | 1.00 | 0.84 | 0.66 | 0.11 | 0.07 | 0.15 |
| B 17 | | | | | | | | | | | | | | | | | 1.00 | 0.77 | 0.21 | 0.24 | 0.00 |
| B 18 | | | | | | | | | | | | | | | | | | 1.00 | 0.22 | 0.20 | 0.15 |
| B 19 | | | | | | | | | | | | | | | | | | | 1.00 | 0.40 | 0.17 |
| B 20 | | | | | | | | | | | | | | | | | | | | 1.00 | 0.40 |
| B 21 | | | | | | | | | | | | | | | | | | | | | 1.00 |

### 3.6. Drivers for energy efficiency

### 3.6.1 Analysis of drivers by average score and frequency of responses

The ranking of drivers is presented in Figure 9, representing the inclusive average scores and frequencies of responses. "Energy blueprint (average score: 0.91)" that refers to long term energy strategy, "Cost saving due to less end usage of energy (average score: 0.85)" and "Rules and regulations (average score: 0.82)" were recognised as the noteworthy drivers to energy efficiency in the industries. 29 out of 36 interviewees deemed energy blueprint at least very important. On the contrary, 28 interviewees considered cost saving due to less energy usage as at least very important. Notably to mention that none of the participants considered both of these aspects as not important. The other vital drivers were "Ambitious individuals", followed by "Arrangement for Energy Management".

Further, the highly ranked drivers point out three significant dimensions which are strategical, financial savings, and lastly regulatory issues. Indeed, the identified facts are very critical to drive and implement not only energy management but also many relevant issues in the broader umbrella of energy. Moreover, the findings also ascertain and emphasize multi-dimensional approaches to industrial energy management [36]. In many cases, energy management are not considered comprehensively in the industries. However, our findings point out the importance to consider multi-dimensional facts towards industrial energy management.

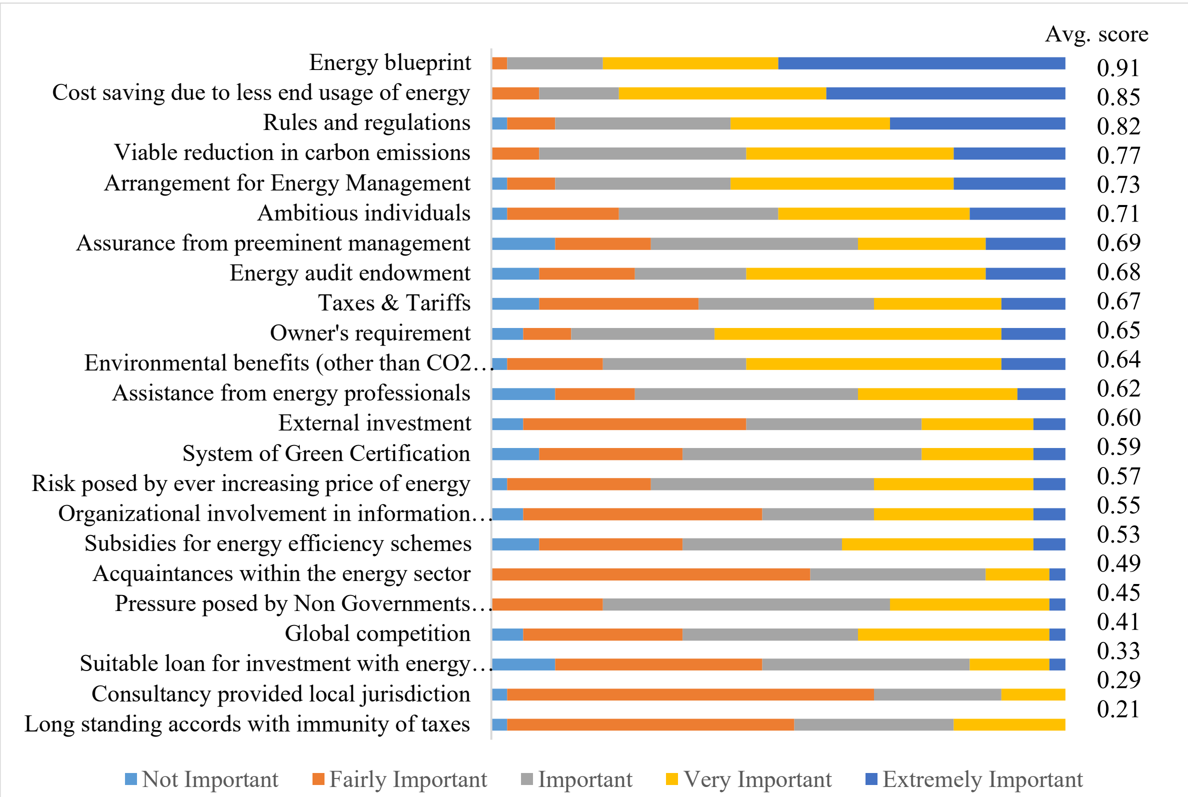


Figure 9. Perceived drivers- frequency of responses

The evidences of this study suggest that a well-designed energy blueprint and regulatory practices could accelerate the journey towards energy efficiency improvement, at the industries in Bangladesh. Furthermore, the concept of energy management being relatively new in the country, there is a clear lack of arrangement for energy management practices.

One significant fact is observed that “acquaintances within the energy sector” and “pressure posed by non-government organisations & clients” are not highly ranked in the list. However, none of the participants has marked these as “Not Important”. Indeed, this is an interesting finding which is contextually significant and indicates the importance of external organisation’s pressure, particularly the NGOs to conform sustainability in an organisation [176]. Besides, we can observe that none of the participants considers the “loan standing accords with immunity of taxes” as extremely important.

In accordance with our findings, previous studies also demonstrated the significance of energy strategy to energy efficiency measures at the industries. Cagno et al. pointed out energy strategy as one of the most important drivers to energy efficiency in the study featuring the Dutch metalworking industry [122]. In a previous study focused at the Swedish industries, energy efficiency policy program is also identified as a significant driver to energy efficiency initiatives [177]. Paramonova et al. discussed the importance of energy policy in the study featuring electricity intensive industries [178]. However, in previous research featuring Swedish foundry industry [116], the presence of ambitious people, as well as long-term strategic energy policy are the most effective means of improved energy management. In earlier study conducted in Ghana, "Lowered cost for lowered energy usage" emerges as the highest perceived driver [25]. In Thailand's manufacturing industry, the reduced production cost was identified as the highest-ranked driver [156]. The study conducted by De Groot et al. [108] focused on the Dutch industries have identified the financial savings due to less energy usage and the implementation of policies such as subsidies and fiscal arrangements as major driving forces toward the adoption of energy- efficient technologies in the industries. The economic feature, precisely, “Cost reduction from lower energy use” were pointed out as the most important driver in Swedish paper and pulp industry [124]. However, in the Italian manufacturing industries, importance of allowances as well as energy interventions financing are identified as significant drivers [136]. The study conducted in another Asian country such as Korea also reflects the financial issues – specifically cost savings – as the major driver towards energy efficiency management [179]. Interestingly to observe that most of the drivers are financial in nature irrespective of industry type. A possible explanation for this similarity is the business and profit driven nature of the industries irrespective of geographical locations.

### 3.6.2 Correlation analysis of drivers

By preliminarily looking at the correlations in Table 11 (red, “very strong” >=0.8; yellow, “strong” >=0.7), we can see that:

- Overall low correlation
- A few correlations within the same categories. In particular:
    - Arrangement for Energy Management (D 5) with subsidies for energy efficiency schemes (D 6): (0.99)
    - Subsidies for energy efficiency schemes (D 6) with assurance from preeminent management (D 10): (0.71)
    - Energy audit endowment (D 8) with Assurance from preeminent management (D 10): (0.72)
    - Viable reduction in carbon emissions (D 7) with environmental benefits (other than $CO_2$ reduction) (D 12): (0.71)
    - Long standing accords with immunity of taxes (D 16) with Assistance from energy professionals (D 17): (0.75)

We can see by observing the major trends in correlation matrix that the arrangement for energy management (D5) seems to represent a potential impact on energy efficiency schemes in the industries (D6). This indicates that energy efficiency related activities may be increased if there is adequate structured process and supporting mechanism. The finding is also confirmed in earlier literature [180] focused on energy management in production system.

In contrast, subsidies for energy efficiency schemes (D6) may have potential impact with assurance from management (D10), which also indicates the impact of support mechanism within organisational framework to promote energy efficiency measures. Nonetheless, we find a high correlation coefficient between carbon emission reductions (D7) with environmental benefits (D12), which is reasonable by considering the multiple benefits stemming from the adoption of energy efficiency solutions [7]. Moreover, the correlation between long standing accords with immunity of taxes (D16) and assistance from energy professional (D17) seems to reflect the beneficial financial benefits related to technical expertise able to support companies in analysing the best energy efficiency solutions.

Table 11. Total sample analysis of correlations. Significant values are represented in bold

| | D 1 | D 2 | D 3 | D 4 | D 5 | D 6 | D 7 | D 8 | D 9 | D 10 | D 11 | D 12 | D 13 | D 14 | D 15 | D 16 | D 17 | D 18 | D 19 | D 20 | D 21 | D 22 | D 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D 1 | 1.00 | 0.40 | 0.17 | 0.00 | 0.25 | 0.26 | 0.29 | 0.24 | 0.14 | 0.31 | 0.01 | 0.29 | 0.31 | 0.27 | 0.03 | 0.18 | 0.19 | 0.02 | 0.14 | 0.13 | 0.13 | 0.01 | 0.25 |
| D 2 | | 1.00 | 0.40 | 0.22 | 0.35 | 0.37 | 0.58 | 0.51 | 0.48 | 0.29 | 0.08 | 0.36 | 0.23 | 0.26 | 0.07 | 0.29 | 0.31 | 0.03 | 0.03 | 0.00 | 0.01 | 0.15 | 0.19 |
| D 3 | | | 1.00 | 0.53 | 0.13 | 0.29 | 0.12 | 0.10 | 0.19 | 0.26 | 0.13 | 0.03 | 0.03 | 0.05 | 0.02 | 0.14 | 0.11 | 0.10 | 0.07 | 0.06 | 0.22 | 0.38 | 0.01 |
| D 4 | | | | 1.00 | 0.60 | 0.64 | 0.51 | 0.53 | 0.34 | 0.53 | 0.34 | 0.28 | 0.11 | 0.05 | 0.19 | 0.16 | 0.33 | 0.12 | 0.28 | 0.23 | 0.00 | 0.09 | 0.21 |
| D 5 | | | | | 1.00 | **0.99** | 0.64 | 0.63 | 0.48 | 0.69 | 0.46 | 0.66 | 0.33 | 0.43 | 0.46 | 0.65 | 0.71 | 0.47 | 0.53 | 0.39 | 0.30 | 0.22 | 0.36 |
| D 6 | | | | | | 1.00 | 0.69 | 0.62 | 0.46 | **0.71** | 0.46 | 0.64 | 0.29 | 0.37 | 0.47 | 0.65 | 0.72 | 0.46 | 0.53 | 0.42 | 0.32 | 0.20 | 0.31 |
| D 7 | | | | | | | 1.00 | 0.58 | 0.62 | 0.69 | 0.51 | **0.71** | 0.39 | 0.47 | 0.36 | 0.57 | 0.50 | 0.21 | 0.32 | 0.20 | 0.13 | 0.05 | 0.25 |
| D 8 | | | | | | | | 1.00 | 0.54 | **0.72** | 0.45 | 0.69 | 0.43 | 0.50 | 0.36 | 0.61 | 0.46 | 0.23 | 0.29 | 0.26 | 0.14 | 0.06 | 0.23 |
| D 9 | | | | | | | | | 1.00 | 0.50 | 0.23 | 0.58 | 0.25 | 0.40 | 0.45 | 0.35 | 0.42 | 0.25 | 0.35 | 0.19 | 0.20 | 0.15 | 0.25 |
| D 10 | | | | | | | | | | 1.00 | 0.59 | 0.61 | 0.39 | 0.53 | 0.47 | 0.55 | 0.54 | 0.40 | 0.46 | 0.36 | 0.23 | 0.15 | 0.25 |
| D 11 | | | | | | | | | | | 1.00 | 0.63 | 0.51 | 0.49 | 0.57 | 0.49 | 0.39 | 0.37 | 0.26 | 0.33 | 0.03 | 0.10 | 0.09 |
| D 12 | | | | | | | | | | | | 1.00 | 0.58 | 0.77 | 0.60 | 0.80 | 0.59 | 0.44 | 0.37 | 0.27 | 0.14 | 0.08 | 0.07 |
| D 13 | | | | | | | | | | | | | 1.00 | 0.63 | 0.52 | 0.53 | 0.49 | 0.57 | 0.45 | 0.45 | 0.19 | 0.16 | 0.22 |
| D 14 | | | | | | | | | | | | | | 1.00 | 0.56 | 0.66 | 0.46 | 0.43 | 0.41 | 0.33 | 0.25 | 0.25 | 0.07 |
| D 15 | | | | | | | | | | | | | | | 1.00 | 0.57 | 0.59 | 0.69 | 0.68 | 0.56 | 0.55 | 0.51 | 0.27 |
| D 16 | | | | | | | | | | | | | | | | 1.00 | **0.75** | 0.63 | 0.53 | 0.38 | 0.27 | 0.24 | 0.18 |
| D 17 | | | | | | | | | | | | | | | | | 1.00 | 0.71 | 0.74 | 0.42 | 0.28 | 0.18 | 0.30 |
| D 18 | | | | | | | | | | | | | | | | | | 1.00 | 0.77 | 0.68 | 0.53 | 0.53 | 0.24 |
| D 19 | | | | | | | | | | | | | | | | | | | 1.00 | 0.55 | 0.46 | 0.47 | 0.22 |
| D 20 | | | | | | | | | | | | | | | | | | | | 1.00 | 0.67 | 0.65 | 0.26 |
| D 21 | | | | | | | | | | | | | | | | | | | | | 1.00 | 0.69 | 0.42 |
| D 22 | | | | | | | | | | | | | | | | | | | | | | 1.00 | 0.43 |
| D 23 | | | | | | | | | | | | | | | | | | | | | | | 1.00 |

### 3.7 Energy efficiency potential

The questionnaire of this section focused to know about the deflation of energy usage considering all accessible cost-effective technologies at the industries. Majority of the respondents expressed that 5%-6% energy could be conserved with the current technology. Energy efficiency related questions were asked to the participants and usage of energy could be abbreviated by 8%-10% by energy management scheme according to the respondents. The very last query was tied in with rating the noteworthiness of considering a structured perspective for the evaluation options for enhanced energy efficiency. Every participant in this study gave the highest score in this part. However, the respondents suggested considering a system perspective for energy efficiency in the industries.

Relating our findings to textile industries in Bangladesh [19], the improvement indicator is quite significant due to the energy-intensive nature of the industries. This could result in a major reduction in net usage and improvement in energy efficiency. However, there is a significant difference of opinion among the stakeholders as per awareness and policy is concerned. Hence, all the stakeholders agree that overall decisions for assessing the options of energy efficiency is much critical and should be considered from a system perspective.

The ″Energy Efficiency and Conservation Masterplan up to 2030″ and ″Energy Efficiency Action Plan″ were prepared by the Sustainable and Renewable Energy Development Authority (SREDA) of Bangladesh, with a target to save 5.3 Mtoe per year, which costs more than a hundred billion Bangladesh Taka (1 USD = 84 Bangladeshi Taka approximately) every year [151]. Guidelines and agenda for the stakeholders at both residential and industrial level, for energy efficiency and management, were proposed, including provisions to provide incentives, tax exemptions, and subsidies to promote the usage of energy-efficient equipment [19]. SREDA, in collaboration with GIZ (a German organisation), published the Energy Auditing Regulations (EAR) in 2016, which considered the environmental issues like global warming, pollution, population, and transportation, that have a direct impact on the economy [151].

### 3.8 Barriers to Energy Service Companies

#### 3.8.1 Analysis of ESCOs by average and frequency of responses

The barriers to counseling with ESCOs were explored in this research. The participants were requested to rank the hindrances in this regard from ″0: Not important″ to ″1: Extremely important″. The ranking of the barriers as per their inclusive average scores and frequencies of responses are presented in Figure 10.

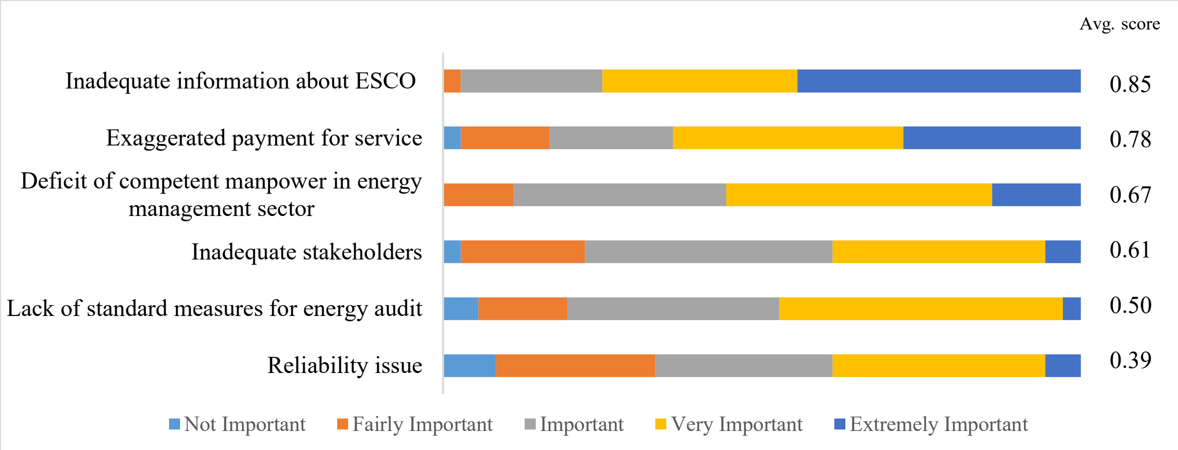


Figure 10. Barriers to counseling ESCOs as per the participants- frequency of responses

The study finds that "Inadequate information about ESCO" is the most significant barrier for consulting ESCOs followed by "Exaggerated payment for service" and "Deficit of competent manpower in the energy management sector". Looking at the result, it can be seen that the industries suffer more in the domain of information and payment issues while incorporating the ESCOs. In fact, most of the industries are unaware of ESCO concept. The energy-related issues are taken care of by in-house electrical or mechanical engineers generally. Considering the present economic growth and industrial transformation, there remains a good business prospect in Bangladesh for the ESCOs, if necessary information and supports are provided to the industries.

By looking at the frequency of responses, we can note that 33/36 enterprises expressed their concern at least as important about competent energy management specialist. Indeed, this is a noteworthy point, keeping in mind that the participants are having a significant amount of industrial experience.

Nonetheless, we should acknowledge that very limited literature has addressed the barriers engaging with ESCOs for energy efficiency and energy management initiatives. More importantly, the concept of ESCO is relatively new in Bangladesh [19], which represents an interesting novelty element of the present study. However, when looking at other industrial contexts, a study on the Swedish Policy Program (PFE) indicates that energy efficiency measures are more dependent on management and operations of technologies, rather than the technology itself [178]. Hence, the ESCOs could become a major stakeholder in energy efficiency, having the potential to make significant contributions by following the similar successful approaches from developed countries [73]. Similarly, previous studies conducted in Italy show that ESCOs present a valuable potential in terms of services offered to drive energy efficiency into companies: however, their potential is yet to be clearly acknowledged by the industry [22]. The preliminary findings of our study seem to suggest that the primary barriers can be overcome through the services of the ESCOs. This indicates a potential gap in the energy marketplace of Bangladesh, offering the first-mover's advantage.

### 3.8.2 Correlation analysis of barriers to ESCOs

By looking at the major correlations in Table 12 (red, "very strong" >=0.8; yellow, "strong" >=0.7), we do not observe any significant finding. Despite this, we can find a slightly interesting relationship between deficit of competent manpower in energy management sector with inadequate stakeholders and lack of standard measure for energy audit with reliability issue. A possible explanation for both of the findings can be drawn:

- The first reflects how the inadequate stakeholders may affect to form expertise in energy management sector.
- The second indicates how the reliability issue may affect standard measures of energy audit.

It should be noted that the studied industries mostly conduct in-house energy audit, as earlier discussed. Therefore, there reliability issue may arise due to energy audit conducted by external stakeholders. However, with our data sample size, caution must be applied, and further research with enlarged sample size could deepen such empirical evidence and explore these preliminary findings.

Table 12. Total sample analysis of correlations. Significant values are represented in bold

| | Inadequate information about ESCO | Exaggerated payment for service | Deficit of competent manpower in energy management sector | Inadequate stakeholders | Lack of standard measures for energy audit | Reliability issue |
|---|---|---|---|---|---|---|
| Inadequate information about ESCO | 1.00 | 0.09 | 0.34 | 0.11 | 0.17 | 0.13 |
| Exaggerated payment for service | | 1.00 | 0.18 | 0.25 | 0.18 | 0.31 |
| Deficit of competent manpower in energy management sector | | | 1.00 | **0.50** | 0.38 | 0.20 |
| Inadequate stakeholders | | | | 1.00 | 0.47 | 0.35 |
| Lack of standard measures for energy audit | | | | | 1.00 | **0.53** |
| Reliability issue | | | | | | 1.00 |

### 3. 9 Summary

This chapter was designed to investigate energy management and its practices, together with barriers and drivers to energy efficiency as well as barriers to ESCOs, in the context of energy intensive industries in a developing Asian economy which, to the best of our knowledge, have been largely overlooked so far. As major remark, our empirical findings show that the concept of energy management and energy efficiency is relatively new in the investigated industries, with lack of awareness and information systems deemed as quite critical for companies. This is particularly critical, as awareness on the importance of energy management and energy efficiency constitute a stepping stone for any further improvement project. In addition, we have observed that absence of energy manager or limited authority of energy manager has impact on barriers to energy efficiency. Nonetheless, the significance of energy monitoring has been pointed out, which is essential for increased knowledge and decision making.

Furthermore, our investigated sample revealed an above-average potential of energy efficiency: this important result call for a greater effort by research, policy-making and industry to boost industrial energy efficiency within developing economies, where too little (e.g. small educational projects, financial loans) has been made so far. Nonetheless, industries are still lagging behind in the implementation of energy efficiency solutions and energy management practices. Interestingly, the present study has pointed out that in the investigated context, companies may be challenged, beyond the well-known technical and economic barriers, also by organisational ones. Further, thanks to a preliminary correlation analysis, we have pointed out in the study several potential correlations among barriers and drivers that could give policy-makers valuable insights on the major obstacles and leverages to promote industrial energy management and energy efficiency. Our preliminary results seem to suggest that further policy-making efforts should be placed to better integrate energy management into industries' organisational structures. Likewise, research should further address organisational barriers and drivers by understanding their role in the decision-making process of adopting an EEM. Additionally, our exploratory findings in a developing economy suggest that research has not yet thoroughly addressed the supply chain of energy services, to better understand the role of ESCOs in designing, delivering and managing EEMs.

# Chapter 4

*This chapter presents a novel framework of industrial energy management services particularly showing the impact of energy management on production resources and operational performances beyond energy savings.*

*This chapter is published in the following conference proceedings and journal:*

*(i) A. S. M. M. Hasan, M. Raza, M. Katic, A. Trianni, "Towards a Framework Linking Industrial Energy Efficiency Measures with Production Resources", IEEE International Conference on Power & Energy System (ICPES), pp. 856–860, 14-17 December 2021, Shanghai, China. DOI: 10.1109/ICPES53652.2021.9683855*

*(ii) A. S. M. M. Hasan, A. Trianni, N. Shukla, and M. Katic, "A novel characterization based framework to incorporate industrial energy management services," Applied. Energy, vol. 313, p. 118891, May 2022, DOI: 10.1016/J.APENERGY.2022.118891.*

## 4. A novel characterization based framework to incorporate industrial Energy Management Services

### 4.1 Introduction

Energy efficiency is increasingly being considered as a major contributor towards energy, economic and overall sustained market performance for industrial organizations [181]–[183]. Thus, being able to recognize, characterize and measure energy efficiency becomes a core capability for such organizations to hold [181]. It comes as no surprise, then, that literature has begun to place a focus in this space. For instance, Patterson [184] investigated the use of thermodynamic energy efficiency indicators encompassing physical and economic issues. Further examples include the energy efficiency index, commonly used as an indicator for measuring energy efficiency in buildings [185], and specific energy consumption (SEC), a widely used measure for energy efficiency within different industrial processes [186], [187], particularly concerning the production of commodities such as steel or cement. Nevertheless, when dealing with manufacturing processes characterized by both large differentiation in the production processes and the variety of final products, energy efficiency measurement and benchmarking may become particularly challenging. Hence, the adoption of energy efficiency measures (EEMs) could represent a valuable indicator of whether a company is effectively improving its energy efficiency [188].

The implementation rate of EEMs has been quite low in recent years [181]. In 2020, the improvement rate of energy efficiency has been much lower (0.8%) than global climate and energy goals [181], [183]. However, the rate of improvement needs to double from current levels to match the gain outlined in the

IEA Net Zero Emissions by 2050 Scenario [4]. Notably, the slow rate of progress in this domain not only has implications on energy itself, but also towards the environment, consumers and businesses [12]. Previous literature [7] has highlighted that a low adoption of energy efficiency technologies and practices imply e.g. reduced lighting, higher noise level, reduced air quality, increase of waste and emissions, increased equipment wear and tear, reduce machines' reliability and availability. At broader level, considering the heavy reliance on fossil fuels for primary energy, lower rate of energy efficiency is adversely impacting the energy security and resource depletion [181], as well as leading to higher emissions of GHG, with adverse impact on climate change [189]. Indeed, as well captured by a report from IEA around capturing the multiple benefits of energy efficiency, the low adoption of energy efficiency has implications that go beyond individual level, thus with sector-wide, national and international perspectives [11]. In fact, a low rate of energy efficiency hinders the achievement of SDGs, in particular, SDG 7 (affordable and clean energy) [190] and SDG 9 (industry, innovation, and infrastructure) [191].

The low implementation rate of EEMs reveals the existence of a large "energy efficiency gap" [15], [31], demonstrating a significant potential for energy efficiency that is yet to be fully explored. However, what this gap also brings to light is the presence of a number of barriers [16], [17] that seem to be acting against their effective adoption. Thus, a deeper understanding of the barriers to industrial energy efficiency is crucial in order for organizations to adopt EM services as well as better grasp the manner in which barriers are rooted within them [192]. This has also been considered in the academic domain where, Sorrell et al. [172], for instance, investigated the occurrence of economic, behavioural, and organizational barriers. Cagno et al. [17], on the other hand, developed an approach to assess barriers to industrial energy efficiency according to seven categories including awareness, technology-related, information-related, economic, organisation, behavioural and competence-related. Indeed, literature has extensively investigated barriers to industrial energy efficiency with a wealth of empirical studies, focusing on both developed [18], [122], [161] and developing economies [25], [110], as well as exploring the moderating role of a number of contextual factors such as industry sectors [27], [29], [133] and firm size [174].

Despite a considerable focus on technical application [193], literature concerning the energy efficiency gap has also started to consider management issues [178]. In this case, theoretical and empirical contributions on themes including energy management practices and energy management services (EMSs) have begun to emerge. Authors including Trianni et al. [26], for instance, have developed a framework for benchmarking the adoption of energy management practices. Fleiter et al. [85] provided a detailed characterization of EEMs by integrating twelve features, emanating from technical, relative advantage and informational aspects, including energy management issues. In contrast, Sorrell [88] focused on energy service contracts, encompassing a customer perspective. Additionally, Benedetti et al. [89] developed a three dimension classification-based framework to highlight energy service contracts.

Considering such research interest, studies also reveal that, among other barriers, EMSs are not being adequately conveyed to industrial decision makers, often attributed to a lack of information and detail over the EMS characteristics themselves [17], [172]. It seems very little efforts are given to both describing them and providing an assessment model for facilitating better industrial decision making [29]. Thus, it appears that research should pay greater attention to comprehensively describe EMSs and understand their impact on production performance. As such, the common avenues (e.g. relationship and impact) between EM and production systems, as well as industrial decision-making procedures in this respect, remain a key issue. In particular, a comprehensive investigation of the nexus between EMSs and operational aspects in industrial organizations is not only crucial in terms of providing decision-support, though also helps to take into consideration the multi-dimensional nature of the industrial sector as a whole [42], [43]. Hence, it appears that a comprehensive identification and characterization of indicators relating to the impact of EMSs on production systems, particularly at the shopfloor, as well as their interactions with other operational features, is a fruitful endeavour for both theory and industrial decision makers.

Given the preliminary background, the present study aims at contributing to this research gap by exploring the following research objectives:

- Characterizing the EMSs in regard to industrial context.
- Developing a framework for assessing industrial EMSs in regard to production resources and productivity attributes within an operational context.

By offering the framework, we intend to highlight not only the EMSs themselves, but also the nexus between the EMSs, production resources and other production features (including production availability, resource management and utilization as well as production process time) in industrial organizations. The framework would benefit both academia and industrial decision makers related to the supply chain of energy efficiency solutions by emphasizing improvement opportunities in their EM activities. Moreover, the framework would also assist engineers operating within industrial organizations by helping highlight the improvement activities in the energy supply chain system.

### 4.2 Literature background

The methodology adopted to analyze existing frameworks that focus on industrial EM and EM services is summarized in Table 13. To date, it seems that theoretical and conceptual studies are commonplace when it comes to industrial EM and energy services. In fact, the idea of EM practices has indeed been addressed through comprehensive studies. However, we observed little attention to energy services and their characterization.

Table 13. Literature review criteria

| Title | Remark |
|---|---|
| Research area | Energy efficiency; Industrial energy management services; Energy management; Energy service framework. |
| Search string | Energy management services; Energy services framework; Industrial energy management; Characterization. |
| Type of Publication | Academic journals, conference proceedings, and book chapters indexed in Scopus and Web of Science. |
| Publication language | English |
| Availability | Full text available online |
| Relevance | Articles focusing on energy management services; industrial energy efficiency proceedings at the institutional perspective |
| Time period | Emphasis has been given to select articles published from the year 2000 until now. |

### 4.2.1 Energy management service concept

Energy management is a comprehensive approach which takes into consideration a wide variety of factors including energy consumption, strategic aspects, managerial issues and people engagement [26]. When it comes to energy services, this phenomenon acts to overcome barriers as well as implement EM and energy-efficient technologies [145]. Energy service is a comparatively new term referring to contractual arrangements featuring energy efficiency at the industrial level. It also includes a financial support scheme towards the adoption of cutting edge technologies [140] and associated services to best support and intervene in industrial plants [145].

Energy service definitions observe a wide focus on themes including integrating energy consumption, commodities, economic features and many more. For example, Greening at el. [194] focused on the manufacturing side, keeping an economic perspective in order to denote energy services. On the other hand, Sorrell et al. [88] emphasized the customer perspective, specifically in the context of multidimensional services. Fell [195] referred to energy services as the activities associated towards energy for obtaining desired end services. In contrast, the definition provided by Bertoldi et al. [145] was more comprehensive, focusing on a wide range of energy services including audit, statistics, project design, implementation, management, operations and maintenance of energy performance contracts [145].

By looking at the available definitions, in this paper we refer to energy management services as the activities, featuring energy management, to save energy by applying EEMs in industrial organizations. It covers multidimensional activities including technical and non-technical measures, methodological approaches, processes, analysis and support aspects, including the financial scheme, keeping focus on industrial EEMs and objectives.

### 4.2.2 EMS model

This section presents an overall review on the existing frameworks of EM, energy services and EMSs. Table 14 presents existing frameworks in the domain of EM and its services.

Table 14. Synopsis of the existing framework focusing EM and energy services

| Authors & Years | Model Narration | Remark | Reference |
|---|---|---|---|
| Sorrell (2007) | Consisted of three variables: "Scope", "Depth", and "Finance". | Emphasized the customer perspective; limited to energy service contracts analysis; lack of focus on operational issues in industrial systems | [88] |
| Benedetti et al. (2015) | Consisted of three dimensions: "Intangibility", "Scope", and "Risk". | Proposed dimensions are applicable to energy services; difficult to comprehend dimensions for all types of energy services. | [89] |
| Kindström & Ottosson (2016) | "Service ladder" concept is applied; service category is divided into four steps; energy efficiency potential & service complexity are the two dimensions considered. | Model emphasizes energy service type and highlights the business model; lack of focus on environmental benefits. | [196] |
| Trianni et al. (2019) | EM practices & services are characterized; attributes are designed based on EM practice, energy efficiency improvement type, target of EM practice, and positioning in the industrial EM settings. | Model is more focused on EM practice characterization and less towards energy services; authors acknowledge lack of attention towards SMEs within the model. | [26] |
| Sa et al. (2015) | Five types of strategies and programs are incorporated; features are reliability, efficiency, cost, funding, and awareness. | Characterization and classification of EMS is lacking; lack of focus on operational issues. | [30] |
| Fleiter et al. (2012) | Includes twelve features referring to technical, relative advantage, and informational aspects. | Energy services are not integrated comprehensively; environmental attributes are not considered; inadequate inclusion of productivity benefits featuring machine, and human resources. | [85] |
| Trianni et al. (2014) | Framework consists of characterization of economic, | EEMs are not conceptualized through an energy service perspective; operational | [86] |

| | | | |
|---|---|---|---|
| | environmental, production, implementation, and interaction related. | performance metrics are inadequately considered. | |
| Bertoldi et al. (2005) | Six strategies are proposed to foster the development of energy services, accreditation system, financing mechanism, contract standardization, and development of third-party financing network. | Study enlists energy services limited to third party financing, energy performance contract, and project financing; lack of focus on the impact of production resources and operational performance. | [145] |
| Kalt et al. (2019) | Conceptualization of energy service cascade model. Components are defined as 'structures', 'functions', 'services', 'benefits' and 'values'. | Lack of focus on industrial energy services; inadequate focus on industrial energy management linking with operational issues (e.g. production resources, operational performance). | [197] |
| Katic & Trianni (2020) | Production resources and operational performances are discussed in terms of energy efficiency measures. | Attributes of production resources and operational performances are not elaborately characterized. | [41] |

The literature review demonstrates that the majority of narrated models place an emphasis on business models, focusing on the customer perspective. Sorrell [88], for instance, focused on energy service contracts incorporating three variables including scope, depth, and finance. However, the model is not comprehensive and mainly focuses on energy service contracts. Benedetti et al. [89], on the other hand, focused on energy service contracts considering three dimensions. Nonetheless, it is quite difficult to understand the relevance of the proposed dimensions for all types of energy services. Kindström & Ottosson [196], in contrast, focused more on the energy service type, incorporating the concept of a "service ladder".

Recently, a characterization-based framework has been derived by Trianni et al. [26] that features EM practices. However, the model is not specifically focused on EMSs. Similarly, Sa et al. [30] suggested strategies towards energy management. The models by Fleiter et al. [85] and Trianni et al. [86] articulated EEMs and contributed to characterizing EEMs. Though, a comprehensive characterization is lacking in either study. Meanwhile, Bertoldi et al. [145] presented strategies to foster energy service development. Nonetheless, it appears a mapping of energy services linking operational management is lacking as well.

The exploration and analysis of the existing models sheds light on several challenging and intertwined issues. Firstly, there is no clear characterization or identification of energy services, specifically industrial EMSs. Considering the significance of energy in the industrial perspective, it is important to prioritize industrial EMSs and their characterization to best support industrial decision makers and other stakeholders in the market.

Secondly, most of the models have discussed energy service contracts and its customer perspective. None of the models examined have clearly referred to the impact of energy services and their implementation in industrial organizations. Moreover, from a strategic point of view, there is very little attention paid towards energy efficiency opportunities, integrating the planning as well as control of production systems, projects and process design.

Thirdly, none of the models examined have integrated energy services with operational management features. For example, the aim of energy services (e.g. improve energy efficiency and better utilization of energy resources) should be integrated in the model with operational management. It is also important to note that the successful implementation of EMSs require integrated approaches that combine operational and strategical considerations, keeping aligned with other sustainability indicators. That being said, the organizations that plan to adopt EM should link their operational activities with their energy efficiency strategy, focusing on the long term objectives concerning sustainable competitive advantage [36], [198], [199]. Moreover, it is necessary to have clear benchmarking for newly adopted technical measures through an EM lens to optimize energy demand [96]. In this context, a synthesized approach towards EMSs is required, integrating the operational features linked to industrial energy efficiency [36].

Fourthly, none of the frameworks analyzed in the EM and services domain have considered the technical features of Industry 4.0 (e.g. real time control and monitoring of machines, use of simulation tools during production planning and the use of Internet of Things in production systems). Researchers predict that exponential progress will be observed in achieving industrial energy efficiency through the adoption of Industry 4.0 technical features, also extensively impacting production processes [200]. Notably, EMSs have already influenced production systems in a larger context. Though, this focus must remain until we have further grasped the energy efficiency and Industry 4.0 nexus. On top of that, energy productivity investment must be associated with EM practices and services [15], [159], [161]. Energy services are acknowledged as a very basic solution; however, little effort has been paid towards characterizing them. More importantly, energy service models aimed at supporting industrial decision makers and featuring detailed actions for better EM are still lacking. Therefore, it is important to consider EMSs, keeping in mind the composite nature of industrial energy systems.

Lastly, EMSs have implications towards asset management [36], [193]. In this context, EMSs incorporate the feature of device control to optimize energy consumption. For example, manual toggling of devices based on requirements is a standard procedure of EM. In recent times, the inclusion of electro-mechanical equipment within industrial organizations brings retrofit benefits which allows for device monitoring that is linked to a specific maintenance scheme, facilitated by the adoption of EM and energy services [193]. Moreover, EM and its services improve accuracy as well response in industrial processes [200], [45]. Unfortunately, the majority of energy services-related studies have sidestepped this retrofit aspect while articulating various frameworks. In this context, attention needs to be paid towards including asset maintenance into the EMS framework.

In summary, we acknowledge that previous studies have investigated several important factors connected to EMS. However, a comprehensive characterization framework is still lacking at industrial level with some key research gaps. In this context, the paper proposes a novel framework of energy management services for key industrial decision-makers and policymakers to comprehensively evaluate the application effect of energy management services. The proposed framework, detailed in the following section, encompasses a novel characterization of industrial EMS, as well as the impact of EMS on production resources and operational features.

### 4.3 A novel framework to characterize EMS

This section presents a detailed characterization framework (see Table 16) incorporating EMSs, their impact on production resources as well as operational attributes. In order to develop a framework integrating the characterization of EMSs, a thorough collection of industrial EMSs is required. Therefore, a collection, review, and selection of EMSs, as well as the methodological steps to develop the framework, have been presented in Figure 11. The first task in building the framework involves listing the EMSs. It should be mentioned that the services are not listed in a random fashion. Rather, we carefully selected the EMSs from relevant papers which are indexed in Scopus and Web of Science. While doing this, we predominantly placed an emphasis on the industrial management perspective. Notably, the categorization of EMSs presented in the study is inspired by the UK carbon Trust [83]. In this case, we define the framework based on an attribute value system that helps to incorporate the industrial decision makers' perspective while assessing an EMS.

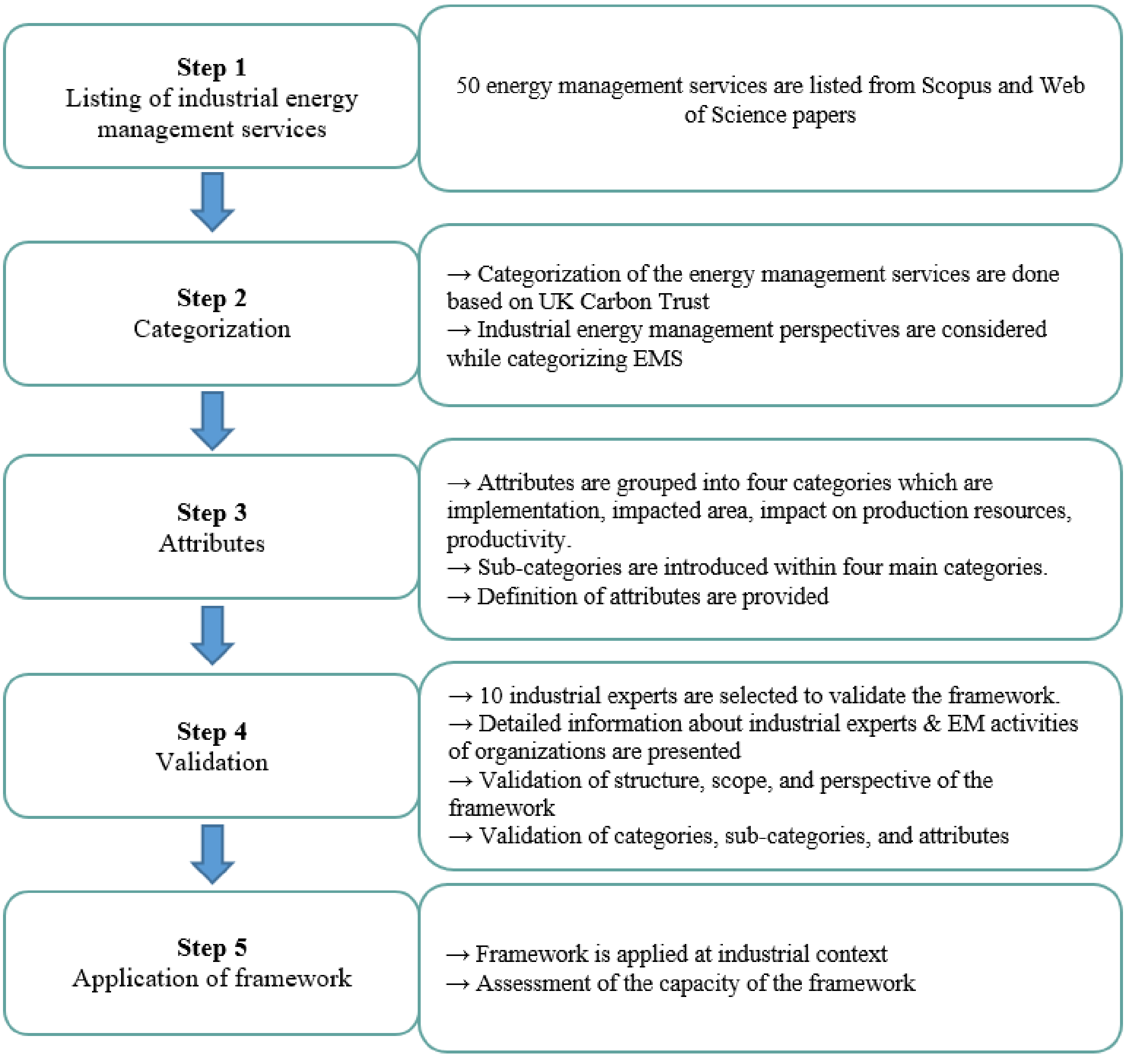


Figure 11. Flow chart of methodological steps

In our framework, the attributes are grouped into four categories: "implementation", "impacted area", "impact on production resources" and "productivity". Later, each of the categories are sub-divided. The categories are selected based on the approach of knowledge representation science [201], which carries a few assumptions. First, we considered the perspective of industrial decision makers whilst selecting the EMSs. Therefore, besides the impacted area and impact on production resources, categories like implementation and miscellaneous are integrated to adequately support the needs of industrial decision makers. Secondly, the categories were integrated by the aggregation of simple attributes which are neither short nor lengthy. Finally, and most importantly, attentions were paid to minimize the overlap among categories.

### 4.3.1 Implementation attributes

The link between implementation-related attributes and EMSs is something that remains quite nascent in extant literature. To help include implementation-related attributes into our study, we based this part of the framework on the learnings from Cagno et al. [202] and Trianni et al. [86]. This helped to facilitate more fine-grained insights concerning EMSs and their implementation-related information, given the aim of this feature is to help key industrial personnel to gain a holistic and comprehensive outlook while assessing the impacts of EMSs. That being said, by implementation we refer to activity type, applicability, ease of service and frequency of an EMS, described below:

***(a) Activity type:*** It is important to know the EM activity type to differentiate decision maker's behaviour [203]. For example, simple repair or retrofit might be easier to implement compared to machinery purchase [204]. Therefore, based on Trianni et al. [86], it is necessary to differentiate between new, retrofitting, optimization and simple management procedures. In this framework, this feature thus differentiates if an EMS constitutes: (1) new activity; (2) optimization of an existing service; (3) retrofitting or (4) simple management procedure.

***(b) Applicability:*** The applicability of EM activities is often discussed in the literature. Thus, taking inspiration from Fleiter et al. [85], two distinct features are considered in this framework including EMSs applicable to (1) all technologies and (2) a specific technology. The first feature is applicable industry-wide, whilst the second is applied to specific processes or technical fields. Distinguishing between these two features is useful, as it allows for a better understanding of the deployment of an EMS.

***(c) Ease of service:*** This feature refers to the ease in which an EMS can effectively be implemented or deployed. Based on Wolfinghoff [205], by ease of service, we refer to the following categories: (1) easy: require minimal effort to implement an EMS; (2) difficult: major efforts are required and (3) dependent: interconnected with other processes and requires support from them for implementation.

***(d) Frequency:*** The implementation of an EMS can be one-time or periodic. Therefore, based on Wolfinghoff [205], this feature can be classified as (1) one time implementation or (2) periodic implementation.

### 4.3.2 Impacted area

An identification of the impacted area in the industrial process is necessary to offer adequate support for decision makers in assessing an EMS. In order to include this aspect in our framework, we have incorporated the attributes related to impacted area based on the work of Fleiter et al. [85]. Here, we have considered the inclusion of impact on input and output processes in this framework, itself seldom observed in EMS adoption considerations. Moreover, the impact of EMSs on the input and output processes allows us to look over the industrial system, not only from a technical point of view, but also from other perspectives (e.g., administrative and supply chain).

***(a) Input:*** In this framework, by “input” as an attribute, we are referring to not only technical aspects, but rather considering the whole industrial process. This may consist of aspects including administrative, supply chain and raw materials, among others. It is important to highlight the impact of EMSs on the overall inputs of the industrial processes, keeping in mind that a decision maker could be interested in understanding the gravity of EMS adoption beyond the technical aspects. In this context, this feature determines if an EMS has an impact on the inputs of a particular production process [206], [207].

***(b) Production process:*** The energy efficiency characterization model by Fleiter et al. [85] incorporated the issue of EEMs linked to core technical processes and ancillary processes. By taking inspiration from Fleiter et al. [85], the production process in this framework is divided into two sub-categories i.e. (1) core technical process and (2) ancillary process. For both of the sub-categories, this feature refers to the impact of an EMS on a core technical or ancillary process.

***(c) Output***: This feature refers to the impact of an EMS on the output of the production process.

### 4.3.3 Attributes related to impact on production resources

Energy management has significant implications on production processes, thus requiring a more detailed illustration of their linkages [61]. The association between production features and EM is also discussed by Sa et al. [30] and Shrouf et al. [60]. Referring to the context, Trianni et al. attributed “productivity” and “operation and maintenance” as two key production features characterizing EEMs [86]. Moreover, Trianni et al. [40] studied the non-energy benefits of integrating EEMs and production resources.

The impact of production resources are categorized into seven segments i.e., machineries and devices [40], capital [208], energy [208]–[210], utilities and building [211], human resources [212], materials and resources [40], [208] and waste [40], [208]. Later on, taking inspiration from previous studies, some of the categories are divided further to show in-depth significance featuring the production resources. For instance, Finman [8] and Worrell et al. [7] suggested that wear and tear on machinery is impacted by implementing EEMs. In addition, EEMs and its impact towards engineering control are also discussed by Finman [8] and Nehler [213].

The detailed description of category and sub-categories of production resources are presented in Table 15.

Table 15. Categories, sub-categories of production resources

| Category | Sub-category | Remark |
|---|---|---|
| Machineries and devices | Wear and tear on machinery | The damage that inevitably occurs due to continuous usage of machinery [214]. In this study, this term refers to the impact of an EMS on the wear and tear of machinery. |
| | Control & monitor | Refers to the process of assessing performance as well as taking necessary steps to ensure that machines are working properly in a production plant [215]. This feature refers to the impact of EMSs on the control and monitor of machines. |
| | Regular maintenance | Refers to the impact of EMSs on scheduled maintenance work of machines and devices in a production plant [215]. |
| | Lifetime | This relates to the total time span of a machine or device in which it is in a workable state. By this feature, we differentiate the impact of an EMS on the lifetime of a machine. |
| Capital | | This refers to the monetary resources entitled in the industrial processes [45]. In this study, it differentiates if an EMS has an impact on monetary resources. |
| Energy | Generation | Refers to the generation of electrical power from primary energy sources [216]; here it differentiates if an EMS has an impact on energy generation. |
| | Consumption | This feature differentiates if an EMS has an impact on energy consumption. |
| Utilities & building | HVAC system | Refers to heating, ventilation and air-conditioning systems applied in the industrial premises [217]. This differentiates the impact of EMS on HVAC systems. |
| | Layout | This refers to the physical arrangement of industrial facilities (e.g. machines and devices, equipment and service departments) [218]. |
| Human resources | Manager | Refers to the person who is responsible in managing the production resources (e.g. staff, machine and raw materials) in industrial plants. This feature refers to the impact of an EMS on managerial position holders. |
| | Staff | Refers the impact of an EMS on the staff who are working within the organization under the supervision of a manager [219]. |
| Material & resources | Raw materials | Refers to the impact of an EMS on raw materials in the industrial system. |
| | Natural resources | Refers to the impact of an EMS on the natural resources in the industrial system. |
| Waste | | Refers to the industrial waste produced during industrial activities. This category includes hazardous, non-hazardous, and emissions as waste [52], [53]. By this feature we differentiate the impact of EMSs on waste. |

### 4.3.4 Productivity attributes

In industrial systems, productivity is one of the more significant parameters to consider. This can be articulated as a relationship between output (e.g. goods, service) and input (e.g. labour, capital, energy) [8]. Improving productivity has always been the goal in industrial systems. Several studies have identified the linkage between energy efficiency and improved productivity [10], [101]. Pye and McKane [101], for example, have discussed productivity even beyond energy efficiency, providing a link to investment decisions. However, taking inspiration from Finmann and Laitner [8] and Worrell et al. [7], we have incorporated three attributes under the umbrella of productivity i.e. availability, reliability, and process cycle.

***(a) Availability***: As with Brall [220], by availability we refer to the ratio of actual production time and total planned production time. By this feature, we determine the implications of EMSs on availability; classified as: (a) strongly positive; (b) positive; (c) negative or (d) not available.

***(b) Resource utilization and management***: Based on Sueyoshi & Goto [221], this feature points to the management of production resources and how efficiently the resources are being utilized during the various phases of industrial operations. In this study, the impact of EMSs on resource management and utilization is listed as (a) strongly positive; (b) positive; (c) negative or (d) not available.

***(c) Throughput***: By considering "throughput", we refer to the frequency of production within the industrial environment. Throughput is a measurement of comparative effectiveness of operational activities. It represents the output rate in the industrial context and quantifies how quickly products can be produced or developed [222]. In this framework, the impact of an EMS on throughput is classified as (i) strongly positive; (ii) positive; (iii) negative or (iv) not available.

***(d) Process cycle time***: The process cycle time refers to the total time (beginning to end) in the industrial production process [223]. By this feature, we refer to the impact of an EMS on process cycle time classified as: (i) strongly positive; (ii) positive; (iii) negative or (iv) not available.

In Table 16, considering previous studies [26], [86], we have provided an application of the novel framework to an extensive list of EMSs. This was accomplished by including values determined from literature that consider some of the features of EMSs and their corresponding impact on production resources. In this regard, we would like to acknowledge the list is not intended to be exhaustive. However, deemed broad enough for a detailed explanation of the features of the proposed framework. Of course, it is important to note that the novel framework has been designed to support industrial decision-makers in the understanding of the features of EMSs and their impact on production resources, therefore attempting to offer a set of valuable perspectives to characterize and assess them. Hence, for the specific decision-making process of adopting a particular EMS in each context, more tailored and detailed information about the considered EMS and its impact on the specific production resource is deemed necessary for accurate decision-making. Furthermore, in a specific application within a company, or with respect to a single EMS, the effective values of the impacts on operations may vary, also subject to a number of contextual factors (e.g., sector, firm size, energy intensity type).

## Table 16. The characterization framework incorporating the industrial EMS

| Notation | Energy Management Services | Category (1) | | Implementation | | | | Impacted area | | | | Impact on production resources | | | | | | | | | | | | | | Productivity | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Production process | | | Machineries | | | | | Energy | | Utilities & building | | Human resources | | Material & resources | | | | | | | |
| | | | Reference (a) | Activity type (2) | Applicability (3) | Ease of Service (4) | Frequency (5) | Input (6) | Core technical process (6) | Ancillary process (6) | Output (6) | Wear & tear on machinery (6) | Control & monitor (6) | Regular maintenance (6) | Lifetime (6) | Capital (6) | Generation (7) | Consumption (7) | HVAC system (6) | Layout (6) | Manager (6) | Staff (6) | Raw materials (6) | Natural resources (6) | Waste (6) | Availability (8) | Resource management & utilization (8) | Throughput (8) | Process cycle time (8) | Reference (b) |
| EMS 1 | Project Identification & appraisal | O | [18] | N | A | Dep | O | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | H | N/A | N/A | N/A | N/A | H | L | N/A | N/A | N/A | N/A | N/A | N/A | N/A | |
| EMS 2 | Project technical design & efficiency upgrade | O | [18], [224], [225] | N | S | Dep | O/P | H | H* | H* | H | H* | L | H | H* | H | Y | Y | H | H | H | H | H | H | H | SP* | SP | SP | SP* | [87], [213] [99] |
| EMS 3 | Project implementation & management | O | [18], [224] | N | S | Dep | O | H | H | H | H | H* | M | H | H | M | Y | Y* | H | L | H* | H* | H* | H | M* | SP | SP | P | SP | [18], [101] |
| EMS 4 | Third-party financing | E | [18], [161], [145], [140], [226], [88], [196], [227] | N | A | Dep | O | M | N/A | N/A | M | N/A | N/A | N/A | N/A | H* | N/A | N/A | N/A | N/A | M | L | N/A | N/A | N/A | N/A | N/A | N/A | N/A | [18], [225] |
| EMS 5 | Operation & maintenance of production equipment to reduce energy use | T | [18], [228], [229] | P | S | E | P | H | H* | H | H | H* | H* | H* | H | M | N/A | Y | H | L | H | H | H | M | H* | SP | P* | P | P* | [85], [103], [213] |
| EMS 6 | Guarantee of performances | O/T | [18] | N | S | Dep | O | H | H | M | H | H | H | H | H | L | N/A | N/A | N/A | N/A | H | M | M | N/A | N/A | SP | SP | P | P | |
| EMS 7 | Purchases of fuel/ electricity | E | [18] | N | A | E | P | M | H | L | N/A | N/A | N/A | N/A | N/A | M | Y | N/A | N/A | L | L | L | M | N/A | H | P | N/A | N/A | N/A | |
| EMS 8 | Insurance coverage | E | [18] | N | S | Dep | O | L | N/A | N/A | N/A | N/A | N/A | H | H* | H | N/A | N/A | N/A | N/A | L | L | N/A | N/A | N/A | P* | SP | P | P | [7], [10], [230] |
| EMS 9 | Energy advice | T/I | [88] | N | A | Dep | P | N/A | M | L | N/A | H | H | M | H | N/A | Y* | Y* | H | N/A | H | H | N/A | N/A | M* | P | SP | P | SP | [231] |
| EMS 10 | Energy audits & analysis | T | [7], [15], [24], [88], | N | A | Dep | P | N/A | H* | M* | N/A | H | H | M | H | M* | Y | Y | H | N/A | H | M | N/A | N/A | H* | P | P* | P | SP | [137], [232], [233] |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | [38], [43]–[45] | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| EMS 11 | Ventilation | T | [88] | O | S | E | O | H* | M | L | M* | M | M | M | H | M* | N/A | Y | H | M* | H | H | N/A | H | N/A | P | P | P | P | [234], [202], [205] |
| EMS 12 | Space heating | T | [235], [88], [224], [236], [237] | O | S | E | O | M | M | L | M | N/A | N/A | N/A | H | M* | N/A | Y | H | M* | H | H | N/A | H | N/A | P | P | P | P | [234] |
| EMS 13 | Steam/hot water | T | [89] | O | S | E | O | M | L | L | L | N/A | N/A | N/A | N/A | M | N/A | Y | N/A | N/A | M | H | N/A | M | N/A | P | P | P | P | |
| EMS 14 | Cooling | T | [88], [237], [89] | R | S | E | O | H | M | L | M | H | M | M | M | M | N/A | Y | H | M | H | H | N/A | H | N/A | P | P | P | P | |
| EMS 15 | Industrial lighting | T | [235], [88], [224], [236], [237], [238] | R | S | E | O | L | L | L | L | N/A | N/A | N/A | N/A | M* | N/A | Y | H | H* | M | H | N/A | H | N/A | P | P | P | P | [128] |
| EMS 16 | Energy performance contracting | O | [161], [145], [88] | N | A | Dep | O/P | H | H | M | H | M | H | M | M | H* | Y | Y* | H | N/A | H | H | H | N/A | H | P | SP | P | SP* | [213], [239] |
| EMS 17 | Data collection about energy saving | I | [228], [229] | P | A | E | P | N/A | L | L | N/A | N/A | N/A | N/A | N/A | L | N/A | Y | N/A | N/A | H | M | N/A | N/A | N/A | P | P | P | P | |
| EMS 18 | Data collection about carbon mitigation policies | I | [228], [229] | P | A | E | O | L | N/A | N/A | N/A | N/A | N/A | N/A | N/A | L | N/A | N/A | N/A | N/A | H | L | N/A | N/A | N/A | P | P | P | P | |
| EMS 19 | Establishment of EM institution with dedicated staffs | O | [228], [229] | N | A | Dep | O | M | L | L | N/A | N/A | N/A | N/A | N/A | H | N/A | N/A | N/A | N/A | H* | H* | N/A | N/A | N/A | SP | P | P | P | [55], [56] |
| EMS 20 | Set-up organization's internal regulations about energy saving & carbon reduction | P | [228], [229] | N | A | Dep | O | H* | H | H | M | N/A | N/A | H | N/A | L* | N/A | N/A | N/A | N/A | H* | M* | H | N/A | H | SP | SP | P | SP | [19], [240] |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EMS 21 | Modification/ adjust of current energy consumption trend by incorporating cleaner energy | T | [228], [229] | O | S | Diff | P | H | H | M | N/A | H | M | M | N/A | H | Y | Y | H | N/A | H | L | H | H | H | SP | SP | N/A | SP | |
| EMS 22 | Investment on production facilities upgradation to ensure energy savings | E | [225], [228], [229], [241] | N | S | Diff | P | H* | H* | H* | H | H* | H* | H* | H* | H* | N/A | Y* | M | H | H | M | H | H | H* | SP* | SP* | P | SP | [10], [17], [242] |
| EMS 23 | Investment at new production facilities for minimization of energy usage & carbon emissions | E | [225], [228], [229], [241] | N | S | Dep | O | H* | H* | H* | H | H* | H | H | H | H | N/A | Y* | M | H | H | M | H | H | H* | SP* | SP | P | SP* | [10], [17], [242] |
| EMS 24 | Installation of monitoring devices for highly energy consuming equipment | T | [228], [229] | N | S | E | O | N/A | M | M | N/A | L | N/A | M | H | H | N/A | Y | N/A | M | H | L | N/A | M | M | P | P | P | P | |
| EMS 25 | Eco-designing | T | [228], [229] | R | S | Diff | O | H | H | H | H | M | L | N/A | H | H | N/A | Y | M | M | M | M | H | H | H* | P | P | N/A | P | [243] |
| EMS 26 | Modification and development of energy efficient products | T | [228], [229], [244] | R | S | Diff | O | H | H* | H* | H | H* | L | N/A | N/A | H* | N/A | Y | N/A | N/A | M | L | H | N/A | H* | SP* | SP | P | SP | [128], [209], [233], [245] |
| EMS 27 | Training & seminar to raise energy savings awareness among employee | A | [228], [229] | P | A | Dep | P | M | H* | H* | M | N/A | N/A | M | H | M | N/A | Y | H | N/A | H* | H* | N/A | N/A | H | P | P | P | SP | [123] |
| EMS 28 | Engage employees in energy-saving activities in daily basis (such as lighting, air-conditioner, etc.) | A | [228], [229] | P | A | Dep | P | M | L | M | L | N/A | M* | M | H* | L | N/A | Y* | H | N/A | H | H* | N/A | N/A | H* | P | P* | P | P | [202], [246], [247] |
| EMS 29 | Energy savings pilot project | T/O | [228], [229] | N | S | E | P | H | H | H | M | H | L | M | H | M | Y | Y | M | N/A | H | H | H | N/A | H | P | P | N/A | SP | |
| EMS 30 | Benchmarking | O | [189], [248] | P | A | E | P | H* | H* | H* | H | L | N/A | H* | H | L | N/A | Y | M | L | H | M | H | M | H | P | P* | SP | SP | [60], [189] |
| EMS 31 | Energy policy & regulation information collection & analysis | I | [145], [196], | P | A | Diff | P | M | L | L | L | N/A | N/A | N/A | N/A | L | N/A | Y* | N/A | N/A | H | L | N/A | N/A | N/A | P | P | N/A | P | [250] |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | [249] | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| EMS 32 | Optimization & control of operational parameters | T | [241] | O | S | Dep | P | H | H* | H | H | H | M | H | H | H | N/A | Y | H | N/A | H | M | M | N/A | H | SP | SP | P | SP | [26] |
| EMS 33 | Optimization of logistic services focusing energy usage reduction | T | [228], [229], [244] | O | S | E | O | M | M | M | H | N/A | N/A | M | M | H | N/A | Y* | M | N/A | H | M | M | N/A | H | P | P | N/A | SP | [26] |
| EMS 34 | Optimization in energy procurement | E | [241] | O | S | E | O | H | L | L | M | N/A | N/A | N/A | N/A | H | Y | Y | N/A | N/A | H | L | M | N/A | M | P | P | N/A | P | |
| EMS 35 | Energy performance monitoring and evaluation | I | [43], [88], [244] | P | A | E | P | N/A | M* | L | N/A | N/A | M* | M* | N/A | N/A | Y | Y* | N/A | N/A | H | L | N/A | N/A | M | P* | P | P | P | [42], [43], [60], [88], [251] |
| EMS 36 | Energy efficiency capital budgeting | E | [42] | N | S | Dep | O | H | H | H | H | M | L | M | N/A | H* | Y | Y | H | N/A | H | L | H | N/A | H | SP* | SP* | P | SP | [7], [8], [10], [87] |
| EMS 37 | Procurement of green energy | E | [30], [229], [244] | N | S | E | O | M | L | N/A | M | N/A | N/A | N/A | N/A | H | Y | N/A | N/A | N/A | L | L | H | N/A | H | P | P | N/A | P | |
| EMS 38 | Cleaner energy | T | [225], [241] | N | S | Dep | O | M | L | N/A | M | N/A | N/A | N/A | N/A | H | Y | N/A | N/A | M | L | L | H | M | H | P | P | N/A | P | |
| EMS 39 | Energy performance reporting | I | [252] | P | A | E | P | N/A | L | L | N/A | M | N/A | M | M | N/A | N/A | Y* | L | N/A | H* | L | N/A | N/A | L | P* | P | P | P | [178] |
| EMS 40 | Procurement of energy efficient equipment | E | [68], [253] | N | A | E | O | H* | H | H | H* | N/A | N/A | H | H | H* | N/A | Y | H | L | M | L | M | H | M* | SP* | SP* | P | SP | [7], [8], [10], [87] |
| EMS 41 | Procurement of energy | E | [241] | N | A | E | O | M | L | L | M | N/A | N/A | N/A | N/A | H | Y | N/A | N/A | N/A | L | L | H | N/A | H | P | P | N/A | P | |
| EMS 42 | Maintenance (preventive/predictive) | T | [224], [225] | P | A | E | P | H* | H* | H | H* | H* | L | H* | H* | M | N/A | Y | H | N/A | H* | H* | N/A | H | M | SP | SP | SP | SP | [42], [60], [178] |
| EMS 43 | Evaluation of energy savings | I | [224], [225] | P | A | E | P | N/A | L | L | N/A | L | L | L | N/A | N/A | N/A | Y* | N/A | N/A | H | L | N/A | N/A | L | P | P | P | P | [251] |
| EMS 44 | Property/ facility management | O | [224] | P | A | Dep | O | L | L | L | L | L | L | H* | H | L | N/A | Y | H | L | H | M | H | M | N/A | SP* | SP | P | P | [145] |
| EMS 45 | Follow up energy efficiency projects | O | [225], [241] | P | A | E | P | L | L | L | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | H | L | N/A | N/A | N/A | P | P | N/A | P | |
| EMS 46 | Demand side management | T | [227], [241], [254] | O | A | Diff | P | H | H | H | H | H | H | H | N/A | M | Y | Y* | H* | N/A | H | H | H | M | H | P | P | N/A | SP | [60], [251], [255] |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EMS 47 | Project financing | E | [145], [38] | N | A | Diff | O | H | N/A | N/A | M | N/A | N/A | N/A | N/A | H* | N/A | N/A | N/A | N/A | H | L | H | N/A | N/A | P | P | P | P | |
| EMS 48 | Production scheduling | T | [61] | O | A | E | P | H | H | H | H | H | H | H* | H | M | Y | Y* | H | N/A | H | H | H | H | M* | SP | SP | N/A | SP | [60], [37] |
| EMS 49 | Marketing of energy efficiency actions | A/I | [43] | R | A | E | P | L | N/A | N/A | L | N/A | N/A | N/A | N/A | L | N/A | Y | N/A | | H | H | N/A | N/A | N/A | P | P | N/A | N/A | |
| EMS 50 | Measurement of emission/GHG/$CO_2$ | I | [30], [254] | R | A | E | P | L | L | L | L | L | L | N/A | N/A | N/A | Y | Y | N/A | N/A | M | L | N/A | N/A | H | P | P | N/A | P | |

(1) Reference (a) refers to the literature backup of energy management services.
(2) Reference (b) refers to the literature backup of asterisk (*) marked
(3) Organization (O); Economic (E); Technical (T); Policy (P); Information (I); Awareness (A)
(4) New activity (N); Optimization of an existing service (O); Retrofitting (R); Simple management procedure (S)
(5) All technologies in general (A); Specific technologies (S)
(6) Easy (E); Difficult (Diff); Dependent (Dep)
(7) One time implementation (O); Periodic implementation (P)
(8) High (H); Medium (M); Low (L); Not-available (N/A).
(9) Yes (Y); No (N); Not-available (N/A).
(10) Strongly positive (SP); Positive (P); Negative (N); Not-available (N/A)

### 4.4 Framework validation

The framework is validated in order to demonstrate its potential for assessing industrial EMSs. By validating the framework, we can test its ability in describing additional information about industrial EMSs to support industrial decision making. In this case, the on-field validation includes a consideration for contingency factors assuming high relevancy, not targeting comparative exploration of cases [148]. The exploratory nature of the study has called to validate the framework through a case study approach [148]. Semi-structured interviews have been conducted based on an interview protocol [256]. This approach was deemed necessary to encompass a comprehensive set of features associated with EMS adoption, an understanding of which proves particularly complex.

When it comes to sample size, previous research deemed a sample consisting of 6 to 10 participants to be acceptable for the initial validation of exploratory studies, keeping a focus on theoretical perspective rather than statistical aspects [257], [258]. In this study, 10 participants are interviewed. Our interviews have been conducted involving industrial experts within Australia. The interviewees were selected based on their relevant experience in industrial EM. More in detail, the interviewees were initially contacted via e-mail, asking for their availability and willingness to participate in the research. We also collected secondary information on their firms. Semi-structured interviews were conducted with each participant, using an interview protocol [256]. We asked to interview individuals that are able to provide valuable insights regarding the provision and implementation of EMSs into industrial companies and their potential impact on production resources [256]. The duration of each interview was approximately 45 to 50 minutes.

Table 17 presents detailed information concerning the sampled interviewees. All interviewees presented an experience and working tenure within industrial energy efficiency and energy management of at least 10 years (in some cases up to almost 30 years), therefore giving sufficient confidence of the reliability of the considerations and insights provided [259]. In addition, their position within their companies (such as Chief Technical Officer, Senior Resource Management Advisor, Principal Carbon Management, etc.) places them in an ideal position to provide a broader view over EMS adoption with implications on other production resources, particularly interesting for the purposes of the study.

Table 17. Data of the sampled experts on industrial EM towards on field validation

| ID | Interviewed designation | Main activity of interviewee | Experience of interviewee | Activities of concern organization | EM status in firm |
|---|---|---|---|---|---|
| S1 | Senior Resource Management Advisor | Involved in energy efficiency programs & sustainable energy. | 13 years of working experience in energy efficiency field. | Biological and physical removal processes for wastewater treatment. | Dedicated energy manager; consults EMS with external stakeholders; no standalone EM policy but follows short & long term EM goals; organize training for employees on need basis; energy audit is conducted; external contractor involved to support the audit services. |
| S2 | Chief Technical officer | Consultation on energy procurement, bill management & reporting, operational data analysis & dash boarding, energy efficiency opportunities, energy/carbon intensity foot printing and emission reduction. | Nearly 30 years of working experience in energy field. | Technical solution provider for electricity and heat. | No dedicated energy manager; consults EMS with external stakeholders; no standalone EM policy; In-house EM. |
| S3 | Resource Management Advisor | Involved in energy efficiency programs; especially in value chain for renewable assets from implementation to operation, optimization and maintenance. | 12+ years of working experience in energy efficiency field. | Treatment of wastewater. | Full time energy manager; short & long term EM goals; organize training for employees on need basis; energy audit is conducted. |
| S4 | Chief Technical officer | Consultation on EM & reporting, operational data analysis, energy efficiency opportunities. | More than 17 years of working experience in energy efficiency field. | Energy advice; energy resources management and utilization; Carbon footprint management and emission reduction. | Full time energy manager; short & long term EM goals; organize training for employees to raise awareness about energy; energy audit is conducted. |
| S5 | Co-founder & energy | Involved in consultation activities, mainly, EM programs consisting of asset management, monitoring and analytics system. | 10+ years of working experience in the field of energy efficiency. | Managing resources, specially the assets in the | No dedicated energy manager; consults EMS with external stakeholders; no standalone EM policy; In-house EM. |

| | | | | | |
|---|---|---|---|---|---|
| | productivity specialist | | | industrial premises using smart integrated device. | |
| S6 | General Manager | Responsible for key functions to drive commercial outcomes, digital innovation & enterprise transformation in energy sector. | More than 10 years of working experience in the field of energy. | Managing of energy infrastructures; energy service provider. | Dedicated energy manager; consults EMS; EM policy along with short & long term EM goals; organize training for employees on need basis; energy audit is conducted. |
| S7 | Co-founder & Managing Director | Involved in energy connectivity programs; energy advice; sustainable energy analyst. | 12+ years of working experience in the field of energy. | Energy provider; fabrication services to the mining & resources. | No dedicated energy manager; consults EMS with external stakeholders; in-house EM. |
| S8 | Associate | Responsible for energy policy preparation; technical assessment of clean energy technologies & energy efficiency projects. | 16+ years of working experience in EM field. | Consultation and financing on energy procurement. | Dedicated energy manager; consults EMS; short & long term EM goals; organize training for employees on need basis; energy audit is conducted. |
| S9 | Chief Executive Officer | Involved in EM projects; consultation on energy efficiency opportunities. | 13+ years of experience in EM & technology field. | Energy efficient solution provider; energy advice; policy; energy system analyzation. | No dedicated energy manager; consults EMS with external stakeholders; no standalone EM policy; In-house EM. |
| S10 | Principal Carbon Management | Responsible for EM projects; implementation of clean energy technologies; consultation on energy efficiency scopes. | More than 13 years of experience in energy & sustainability field. | Extraction & processing of minerals, oil and gas. | Full time energy manager; consults EMS with external stakeholders; short & long term EM goals; organize training for employees on need basis; energy audit is conducted. |

Interviews were aimed at collecting information regarding the participants' respective organization, including the company profile (general company description and number of employees); product and process (information about products produced, main production processes and production volume); EM (information about integrating a full-time Energy Manager, external consultation about EM, EM policy, training and energy audits) and several judgements about the framework in terms of completeness, usability and ease of use. Completeness is projected as a cluster of properties to identify whether: (i) the categorization is clear; (ii) the attributes cover all relevant performance aspects; (iii) the attributes are distinct; and (iv) attributes are sufficiently levelled. On the other hand, usability aimed to test the attributes for identifying the impact of EMS adoption; better organization of EMSs; valid help to manage the EMSs and select suitable EMSs based on organizational strategy. Finally, in the ease of usage section, we have investigated the ease in which the participants perceived the usage of the framework to be and, ultimately, its worth in application when it concerns industrial organizations.

The results of the on-field validation of the framework are presented in Table 18. Referring to completeness, it was largely confirmed in a positive manner. Notably, the interviewees marked no overlapping, referring to the categorization of the attributes. Interviewees S2, S4, S5 and S6 highlighted the relevance, particularly referring to the completeness of the attributes. Some interviewees seemed to have some prior knowledge of the attributes incorporated into the framework, but as a comprehensive opinion, the framework helped them to better shed light on what they had in their observance already.

Table 18. Results of the on-field validation

| ID | Completeness | | Usability | | | Ease of Use | |
|---|---|---|---|---|---|---|---|
| | Categorization | Attributes | Identification | Applicability | Valid & quick help | Ease of use | Worth to adopt |
| S1 | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓✓ | ✓✓ |
| S2 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ |
| S3 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓ |
| S4 | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓✓ | ✓✓ |
| S5 | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓✓ | ✓✓ |
| S6 | ✓✓ | ✓ | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ |
| S7 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ |
| S8 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓ |
| S9 | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓ | ✓✓ |
| S10 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ |

*Legend: ✓✓(Positive evaluation); ✓ (Positive evaluation, further suggestions proposed); ✗ (Negative evaluation).

On the other hand, focusing on usability, S1 recognized the attributes as a useful instrument to leverage EMSs, stating that: "*the attributes are comprehensively articulated for providing support to find out the* *nexus among EMS and operational aspects, precisely to the production resources*". The other interviewees, notably S3, S6, S7, S8, and S9, also highlighted the usability of the framework. In contrast, a Chief Technical Officer (S4) related the applicability perspective to the consideration of non-energy benefits, stating that "*financial issues should be incorporated in [a] quantified way to better elaborate the nexus between capital resources and EMS. This might help the industrial managers and decision makers to deeply adopt the framework*". Nonetheless, this does not reflect any flaw of the framework since the aim was not to quantify non-energy benefits, but rather to show the impact of industrial EMS adoption and their respective operational aspects. On the other hand, when it comes to ease of use of the framework, all of the interviewees provided a positive response.

In sum, all of the interviewees evaluated the framework quite positively overall. The interviewees have clearly acknowledged the usefulness towards assessing the EMS in an industrial context. In short, the model is appreciated by the interviewees in terms of approach as well as aptitude of being adopted in industrial firms.

**4.5 Case Study**

A case study is presented in this section aiming to demonstrate an on-field application of the framework. A water treatment company was selected in this context, considering the multi-dimensional as well as intensive nature of energy consumption at operational stages during water treatment. In a water treatment plant, the total energy consumption is attributed to operational energy and energy embodied in infrastructure [260]. In the recent years, researchers have started exploring EM within water treatment plants, considering the significance of the water-energy-GHG nexus [261].

The water treatment company considered in this study is located in Australia. We have carefully selected the case study ensuring the relevance of EEMs in the specific company, the presence of a number of technologies (such as industrial pumps, HVAC, lighting and electric motors) for which energy management and energy efficiency issues could be considered, as well as the knowledgeability of the respondent over industrial energy efficiency issues within the company. Therefore, in the case study considered for the framework, the firm is a large multi-site energy intensive industrial company with a number of similarities with manufacturing industries in terms of cross-cutting technologies in place. This helps to provide a level of concept generalizability and transferability, also towards production and manufacturing industries.

The plant has around 2,700 employees (with additional contractors) and an annual turnover of 2.03 billion USD. Water treatment, sewage transport and treatment, recycling of water, bio-solid and biogas generation from sludge and storm water services are the main activities of the company. The company supplies 1.34 billion litres of water to homes and businesses; recycles 70 million litres and treats 1.31 billion litres of wastewater on a daily basis. The monthly average of stationary fuel consumption in the company is 71,674 litres whilst transport fuel consumption is 2,428,691 litres. Apart from these primary energy sources, the approximate annual electricity consumption is 365 GWh.

The interviewee leads the EM activities and is responsible for energy efficiency projects, energy procurement and inclusion of sustainable energy. The interviewee has been working in the industrial EM domain for nearly 14 years and is profoundly knowledgeable within this sector. Being a part of the management team, the interviewee is involved in operational decision-making processes, which is critical for this study.

By looking at the adopted EMS, we can highlight the company's strengths and critical areas. Firstly, we observe significant commitment to EMSs, energy advice, energy procurement, operation and maintenance as well as optimization of operational parameters. Secondly, the framework highlights adequate focus on project-based services, in particular project implementation and management, energy saving pilot projects and investments on new production facilities. Lastly, the model highlights data collection on energy savings, energy efficiency capital budgeting, engaging employees when it comes to energy saving activities and regulation for energy savings as key areas where the company has scope to improve.

#### 4.5.1 Energy management status

We observe that the company is primarily focusing on technical and energy performance-related EMSs. A good overall approach to EM activities is observed given the company is also aligned with ISO 50001 guidelines. Additionally, top management is involved in EM activities, whereas the mid-level employees are also a part of strategic and operational decisions. However, considering the holistic perspective of EM, the company still has scope for improvement, particularly when it comes to policy and awareness. The key points concerning energy management in the company are presented below:

- Adoption of EMSs consider administrative processes. The productivity benefits are often neglected while decisions are taken to adopt an EMS.
- The EM training appears quite limited in the company. Training on EM is offered to individuals on an as-needed basis.
- Energy audits are conducted once every four years on targeted areas.
- The EMS is mainly oriented towards the water purification and treatment process. However, the company is also engaged and connected to external stakeholders (i.e., Australian Alliance for Energy Productivity and the Water Services Association of Australia) to improve energy efficiency activities.

  The adopted EMS are both internally and externally implemented. The examples of internally adopted EMS are "investment on production facilities", "optimization", etc. In contrast, "energy advice", "energy strategy development", "energy procurement", etc. are often externally adopted.

### 4.5.2 Impacted area on production process

The impacted area due to the adoption of an EMS is generally considered in the company. In particular, the technical management team carefully adopt any EMS considering its possible impact on core technical processes. This highlights an interesting and common tendency from the management perspective to think over core technical processes due to change or adoption of any technical activity. Concerning the water purification and treatment activities, we find the core technical process and ancillary processes are impacted due to several EMSs. For example, the operation and maintenance of production equipment to reduce energy usage significantly influence the production process. Again, the optimization in energy procurement does not seem to directly impact the core technical process; however, influencing the overall input system. It is also important to note that the impact depends on the severity and activity type of the EMS.

### 4.5.3 Impact on production resources and productivity

The detailed impacts on production resources and productivity stemming from the adoption of EMSs in the company are presented in Table 19. By looking at the detailed impact on **production resources**, we find that not all the production resources are being impacted simultaneously. Rather, the impact level is varying case by case, depending on several factors (e.g. type of activity).

The impacts of EMSs on production resources have not been considered comprehensively while adopting any EMS in the company. In fact, the impact on utilities and buildings, human resources as well as material and resources are largely overlooked. By looking at the production resources, it seems that while adopting EMSs, energy has been the only key focus.

However, a few interesting insights are observed with the application of the framework, concerning machinery in particular. For instance, electrical motors and pumps are one of the highest consuming apparatuses in a water treatment plant [261]. To increase the efficiency, experts often suggest the use of efficient motors. With efficient motors, the operational team observed a high impact on machinery, leading to better control of machinery, reduced maintenance as well as improved lifetime of the machine. Again, with another EMS such as project management, the company observed increased hours of staff involvement. The company also observed an impact on capital resources due to project management. Nonetheless, the impact for such cases generally depends on several issues (e.g. project type, volume of activities and intensity of labor involvement).

"Investment on production facilities to minimize energy usage and carbon mitigation", is recently adopted on a broader scale, and the company has observed a significant impact on waste. In fact, in this case, collected sludge from the water treatment process is being used to produce biofuel, which has significantly improved not only the process cycle but also has a positive impact on materials and resources.

Some additional comments were also received during the discussion encompassing the impact on production resources. For example, in recent times the company adopted a few pilot projects related to energy savings. While implementing these projects, the company observed a positive impact on their energy consumption and productivity on a broader scale. However, what is concerning here is that often such pilot projects are not converted into larger projects due to several barriers (i.e., lack of local technical experts and other priorities). This indicates the organizational barriers to industrial EM [29], [110], [122] which remains to be discussed and addressed.

Unfortunately, it is observed that **productivity** features are also neglected while adopting the EMSs. In fact, availability and throughput have been largely overlooked. However, the interviewee acknowledged multiple productivity benefits indistinctly due to EMS adoption, as shown in Table 19.

For example, the company observed a significant amount of energy consumption reduction for the aerators by optimizing the power usage, which eventually improved the process cycle and resource utilization. The interviewee has also acknowledged the benefit of using real-time monitoring devices integrated with state-of-the-art systems in the plant. Considering the volume of data generated by different technical apparatuses, the advance database system also offers critical capabilities to look into the data [262]. By monitoring and analyzing the operational data collected through the monitoring device for the electrical pump and aerator, the technical team uncovered several options to improve the operational performance, with credit to I4.0 and its technical features.

Again, when it comes to production scheduling or planning, simulation technology, a technical feature of I4.0, is identified as a quite significant and powerful tool in the digital manufacturing process. This stems from its capabilities in product validation, including system design and configuration by experimental methods [60]. Simulation also helps to reduce costs by optimizing product development cycles [60]. While applying the framework, the interviewee discussed the application of a simulation tool for production planning in the plant. Such a tool not only helped to save on costs prior to the implementation of any new technology, but also ensured effective resource management and utilization.

The water treatment plant has also adopted preventive maintenance (EMS 42), including condition assessment via a technical asset register system. Preventive maintenance increases the lifetime of a machine and improves the machine performance [263]. The interviewee has acknowledged that preventive maintenance has significantly improved the performance of electrical motors and pumps (e.g. reduced start-up time and defect elimination). Further, it has also reduced sudden or unplanned outage of the motors and pumps leading to increased availability of the machine. In fact, overtime cost due to additional involvement of labour is also reduced due to improved performance of the machine.

In general, preventive maintenance incurs a positive impact on the production process overall due to improved performance of the electrical motor and pumps.

Table 19. Impact on production resources and productivity attributes due to EMS

| Notation | Energy Management Services | Production resources | | | | | | | Productivity | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Machine | Capital | Energy | Utilities & building | Human resources | Material & resources | Waste | Availability | Resource utilization & management | Throughput | Process cycle |
| EMS 2 | Project technical design & efficiency upgrade | **H** | **M** | | | | | | | + | | + |
| EMS 3 | Project implementation & management | | **M** | | | **H** | | | | + | | |
| EMS 5 | Operation & maintenance of production equipment to reduce energy use | **H** | | | | **M** | | | +/-- | + | | |
| EMS 9 | Energy advice | **L** | | **Y** | | | | | | + | | + |
| EMS 10 | Energy audits & analysis | | | **Y** | **M** | | | | | + | | |
| EMS 20 | Set-up organization's internal regulations about energy saving & carbon reduction | | | **Y** | | | | **L** | | + | | |
| EMS 21 | Modification/adjust of current energy consumption trend by incorporating cleaner energy | | | **Y** | | | **M** | **M** | | + | | |
| EMS 23 | Investment at new production facilities for minimization of energy usage & carbon emissions | | | **Y** | | | **M** | **H** | | ++ | + | + |
| EMS 24 | Installation of monitoring devices for highly energy consuming equipment | **M** | | **Y** | | | | | | + | | + |
| EMS 27 | Training & seminar to raise energy savings awareness among employee | | | | | **L** | | | | + | | |
| EMS 29 | Energy savings pilot project | | | **Y** | | | | | | + | + | |
| EMS 30 | Benchmarking | **M** | | | | | | | | | | + |
| EMS 32 | Optimization & control of operational parameters | **M** | | | | | | | + | | | + |
| EMS 35 | Monitoring & evaluation of energy performance | | | | | | | | | + | | |
| EMS 36 | Energy efficiency capital budgeting | | **M** | | | | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EMS 39 | Energy performance reporting | | | | | | | | | + | | |
| EMS 40 | Procurement of energy efficient equipment | | **M** | **Y** | | | | **L** | ++ | | | + |
| EMS 41 | Procurement of energy | | **M** | | | | | | | | | |
| EMS 42 | Maintenance (preventive/predictive) | **H** | | **Y** | | **M** | | | ++ | + | | ++ |
| EMS 43 | Evaluation of energy savings | | | | | | | | | + | | |
| EMS 46 | Demand side management | | | | | | **M** | | | | | |
| EMS 48 | Production scheduling | **M** | | | | | | | + | + | | |

(1) High (H); Medium (M); Low (L);
(2) Yes (Y); No (N);
(3) ++ (Strongly positive); + (Positive); -- (Negative)

## 4.6 Discussion

The study presents a novel framework which allows industrial decision makers to assess EMSs based on the impact of operational features within industrial organizations. Considering the complexity in operational activities, this framework not only provides support towards energy intensive industries, but also significantly contributes to SMEs and other industries which are in the nascent stage of EM. In many cases, industrial decision makers do not consider the impact of EM on production activities and overlook its associated benefits [36], [159], [202]. By considering the framework in their decision-making processes, industrial decision makers can visualize the overall impact of EM on production resources and productivity attributes within an operational context - helping to select the appropriate services to adopt at their respective organizations.

From a theoretical standpoint, it should be acknowledged that the EMSs encompassed within the framework are independent from each other. However, in a few cases, they are performed concurrently. By observing the framework, the listing of the EMSs is not pointing to specific cross-cutting technical sectors, rather focusing comprehensively on the industrial EM domain. Another important point is that the framework mainly focused on the "soft" aspects of EM, meaning excluding co-generation, waste heat recovery and related EMSs. The reason behind such an exclusion is in enabling us to focus more on the managerial and decision-making attributes. This is particularly useful for an assessment of impacts on production resources, of which seems to be neglected in previous frameworks [26], [85].

In our framework, we have observed 22 EMSs, the act of which can be considered a novel endeavor itself. Again, 13 services are categorized as periodic; nine services are labelled as optimization types and six are listed as a retrofitting type activity. The EMS could even be exemplified in a few cases considering the concurrent features of operational performance [61]. In contrasting our findings with another characterization framework by Trianni et al. [86], we observe a high number of new activities (34). Similarly, when it comes to the applicability of the EMSs, 27 services are found to be applicable within industrial process. This indicates that the EMSs are generally applicable for all industrial sectors, also affirmed by industrial experts during the validation phase and the application of the framework. Similarly, when it comes to the ease of implementation concerning activities, 25 EMSs are categorized as easy to implement whereas 18 EMSs are categorized as dependent, referring to implementation dependency with other services and processes.

Despite the growing attention towards industrial energy efficiency, the impact of EM on production processes remains to be adequately addressed [40], [37]. Hence, our findings provide a significant contribution in the energy efficiency and sustainability field by looking at the production processes through the lens of EMSs. By looking at the framework, it can be perceived that 23 EMSs are significantly impacting industrial input processes. Again, when it comes to the impact on a core technical or ancillary process, 21 EMSs are found to have a significant impact. These findings highlight the nexus between EM and production processes in the industrial operational context [264]. When it comes to the industrial output, the majority of cases are related to the aspects of optimization, project-oriented and production based, subsequently also affirmed by industrial experts during the validation and application phase of the framework development.

One of the salient features in the framework is the inclusion of the impact of EMSs on production resources. In this case, the production resource of industrial machinery appears to be particularly intertwined with EMSs [40]. For example, 16 EMSs are found to significantly impact the wear and tear of industrial machinery. Following this, in terms of machine lifetime, there are 14 EMSs which have a significant impact on this factor. Indeed, a few of the EMSs (e.g. project technical design and efficiency upgradation, investment on production facilities upgradation as well as preventive or predictive maintenance) are not only impacting the machine lifetime, but also the regular maintenance activities. When looking at the regular maintenance of machinery, 13 EMSs are identified to have a high influence. One important point to be noted here is that the positive linkage between maintenance activities and EMSs is also supported by scientific literature in the framework [7], [10], [101]. However, considering the way EMSs are implemented, we expected to find a significant relation between control and monitoring of machinery and a few of the EMSs, particularly for maintenance activities, demand side management and production scheduling. In fact, the aforesaid EMSs are significantly impacting all the considered features in the machinery portion of the framework.

While considering economic issues through the lens of industrial energy management, researchers have largely been concerned with “implementation cost” and “payback time” [86], [265]. However, capital investment decisions in industrial organizations also depend on several circumstances (e.g. business opportunity evaluation, savings and available technologies) [193]. Considering energy management service cost, it is essential to assess the economic factors to affirm the choice of an optimum solution. Cost-benefit analysis is an accepted approach in organizations to compare economic sustainability of a probable strategy and potential actions [266], [267]. However, the proposed study aims at showing the existence of a number of implications on production resources that may be important when considering the implementation of an EMS. This is accomplished by proposing a framework to support decision-makers in highlighting them in the first place – acting as a potential first step towards their full quantification, possibly also in economic figures, supported by appropriate metrics.

The adherence of EM and economic issues, in our case the “capital”, is acknowledged both in academia and industry. However, very little studies have focused on the impact of EM on monetary resources. An investigation of the nexus between capital and EMSs is a critical exercise, considering the relationship with business opportunities and expansion activities. Moreover, such an understanding can help facilitate the selection of EMSs that are worth adopting for a particular industry and business type. Indeed, the decisions linked to capital resources are dependent on various circumstances including energy price, environmental factors, subsidies and market issues. As predicted in this study, a high relationship exists for 21 EMSs with regards to capital resources. Notably, EMSs contribute to ensuring guaranteed savings or shared savings [145] in terms of energy as well as monetary value. This was, to an extent, addressed in a recent study on energy services, where Nurcahyanto et al. [144] highlighted several aspects relating to financing mechanisms. However, the specific impact on capital resources and particular EMSs was not considered in this study.

On the contrary, EMSs like data collection, engagement of employees and marketing of energy efficiency actions are identified as having a lower impact on capital. By looking at energy as a production resource from an EMS perspective, we should remember that managing energy is not just a technical challenge. Rather, the idea is to best implement the technical changes whilst maintaining minimum disruption and economic limits [193]. Therefore, the impact of EM will always have a significant impact on energy consumption within industrial organizations. For instance, in the framework we observe that there are a total of 37 EMSs available which are linked with energy consumption. Here, we should keep in mind that most industries, especially manufacturing companies, are operating in a competitive age. Therefore, a small reduction in energy consumption cost could also critically impact the whole production and value chain system. However, while looking at "energy generation", on the other hand, the framework suggests that this is not deeply affected by EMSs, with only 17 of them incurring a notable impact.

In terms of utilities and buildings, EMSs also appear to particularly related, especially to HVAC. By looking at the framework, we observe that 20 EMSs have a strong relationship with HVAC systems. For example, demand side management, production scheduling, operation and maintenance of production equipment as well as efficiency upgradation all have a clear impact on production systems. Besides HVAC factors, the physical layout of industrial organizations have an impact on energy consumption, especially at the manufacturing floor [211]. It is important for industrial organizations to have a physical layout that ensures efficient flow of material and production activities within their operational context [264]. However, when we think of offering EMSs, it does not seem to impact too much on the industrial physical layout where only four of the EMSs are observed to have a high impact. This reduced impact on plant layout by EMSs seem reasonable considering that EMSs are basically representing energy efficiency improvement activities within industrial machineries and operations. As such, production design and layout is not as severely impacted in most cases.

Concerning industrial processes and the supply chain, the role of managers cannot be understated. In fact, the paradigm of sustainability in industrial organizations and their adoption relies intensely on managerial and top management positions [193]. When looking at the framework, it is observed that managers have a significant association with EMSs. To be precise, 38 EMSs are significantly impacting managers in the industrial context. However, when looking at the industrial production chain through the lens of sustainability, this association appears reasonable given managerial context and EM are both intricately linked to the strategic and operational layers in industrial processes, especially at the process layer in production plants [264]. For instance, project implementation and management, production facilities upgradation as well as setting up internal regulations about energy saving all appear significantly dependent on managerial issues and coordination. On the other hand, the level of impact concerning EMSs on line staff might not be as visible as the managerial positions. However, we highlighted 18 EMSs that have a high impact on industrial staff. Interestingly, a few of the EMSs including maintenance, establishment of an EM institution, project implementation and management are equally impacting both the managers and staff. This indicates that the impacts of EMSs on human resources depends on EMS characteristics (e.g. service complexity, strategy and organizational setup).

With respect to the relationship between EMSs and material and resources, there appears to be an inclusive impact, particularly on the raw materials. There are 20 EMSs that have a high impact relationship with raw materials. For example, while considering eco-designing as an EMS, this allows industrial managers and decision makers to rethink their industrial process, hence offering resource efficiency at the design stage [264]. Again, when it comes to energy efficiency capital budgeting, it allows industrial decision makers to consider budgetary expenditure concerning several industrial processes. Interestingly, budgetary issues have a significant impact not only on the industrial processes, but also the raw materials used in the industrial production system. On the other hand, the vast majority of EMSs do not seem to deeply impact the natural resources that are used in the industrial processes. We highlighted only 13 cases that observe a significant relationship between EMSs and natural resources used in industrial organizations.

As stated in Section 4.3, in this study we have considered waste in a broader perspective and hence incorporating hazardous, non-hazardous and emissions inclusively. In this case, 23 EMSs are identified to have a significant impact on the waste stream in industrial organizations. It is important to note that when industrial firms adopt or invest in EM activities to ensure efficiency, we often observe a reduction of waste or $CO_2$ emissions [7]. For instance, an energy audit allows us to inspect and analyze the industrial energy consumption and highlights the energy efficiency improvement options [4] eventually leading to a reduction of waste and emissions in most cases. On the other hand, while looking at other EMSs concerning, for example, engaging employees in energy saving activities on a daily basis or optimization of logistic services to reduce energy usage; it is obvious that there is a high potential towards reduction of waste due to lesser consumption of energy for adopting such services in industrial firms.

Several studies [7], [8], [10] have pointed out the issue of industrial EEMs and productivity benefits. Indeed, this provides an avenue for opening up the Pandora's box in exploring the nexus between EM and industrial productivity. In this context, we can appreciate that the factor of "availability" is impacted by the majority of EMSs. In fact, 41 EMSs are significantly impacting this factor. This insight was facilitated by the detailed knowledge on EMSs by virtue of the developed framework. Additionally, when it comes to the nexus between production reliability and EMSs, the vast majority of EMSs seem to have an impact on production reliability.

All the production resources and productivity features considered in the framework have significant importance within the industrial production system. However, the impact on production resources and productivity attributes due to the adoption of EMSs can vary case by case. In fact, while looking at the framework theoretically as well as the case study application, we have observed that not all of the attributes are impacted simultaneously at the same level. Rather, we find that every EMS is impacting the attributes based on individual perspective, which is expected. For example, the level of impact on the attributes for EMS 2 (projects technical design and efficiency upgrade) and EMS 9 (energy advice) are different. Likewise, the impacts of EMS 26 (modification and development of energy efficient products) on production resources are dissimilar in many cases compared to EMS 23 (investment at new production facilities for minimization of energy usage and carbon emissions). This can be attributed to the fact that different levels of impact on production resources and productivity features reflect different contextual variables (e.g. energy intensity, sectors and firm size) within industrial organizations.

The same logic can also apply in the broader pursuit of minimizing the energy efficiency gap in the context of industrial organizations. Despite the notion that EM helps reduce the energy efficiency gap [15], [268], the extent to which this can be achieved also depends on several contextual phenomena (e.g. industry type, firm size and energy consumption nature). Therefore, a one- size– fits- all approach is not appropriate when it comes to energy savings or energy efficiency gap minimization. An organization might experience different proportions of energy savings, thus leading to the minimization of the so-called energy efficiency gap. However, in a recent study, Hasan et al.[199] suggested that 8-10% of energy savings could be possible with the adoption of energy management practices in industrial organizations.

Whilst looking at the barriers to industrial EM, this framework could also open a few avenues for discussion, which are modelled by previous researchers [18], [43]. For example, previous studies have highlighted various barriers that hinder an explicit consideration for supporting process-related decisions in the context of EM [16], [17]. Therefore, while looking at the implementation of EMSs, companies may broaden their decision-making perspective by integrating the impact of EEMs on the production resources. Observing such a mindset is important, considering that energy is a crucial factor for ensuring resource efficiency, sustainability and competitiveness in the market. Indeed, this introduces a significant, yet initial, finding that has emerged through the comprehensive knowledge on EEMs and production resources gained in this framework.

On a separate note, it should be mentioned here that the fourth industrial revolution, Industry 4.0, also focuses on energy efficiency to minimize the production cost in industrial organizations [269]. Therefore, the impact of EM is critical in organizations for adopting technical features associated with Industry 4.0. More importantly, EM acts as an expeditor for improved energy performance when applying optimization techniques focusing on energy productivity. Nonetheless, queries might arise on the implementation of EMSs within industries due to its multidimensional nature. From the energy productivity perspective, it is obvious that energy efficiency should be incorporated with certain technical features, and clearly, with the adoption of EMSs.

Moreover, whilst looking at Industry 4.0 through the lens of EM and production resources, we find several significant factors in the industrial context, precisely relating to real-time monitoring of the device or industrial machines. For example, in our framework, "energy" is considered as one of the production resources. When we opt for adopting an EMS (e.g. modification and development of energy efficient products, eco-designing and energy saving pilot projects), it certainly has an impact on production resources. Though, in this case the possible effect is energy consumption reduction. With the help of Industry 4.0 technologies, key decision makers can easily monitor or evaluate the impact of EMSs within the entire production system.

### 4.7 Summary

The novel framework presented in this chapter aims to characterize industrial EMSs by considering their impact on industrial operational features. To the best of the author's knowledge, very little studies have focused on industrial EMSs at the same level of detail as accomplished in this framework. Furthermore, there is no prior study that has highlighted the attributes featuring an "impact on production resources" in a comprehensive manner. This is particularly critical for industrial decision makers as it highlights the nexus between production resources and operational aspects. An additional element of novelty is ascertained by having highlighted the need to analyse EMSs as per their diverse perspectives (e.g. resource management and impact on productivity). In particular, undertaking a characterization of the attributes allows to provide an inclusive view of relevant EMS perspectives and results in the consideration of a more specific mechanism underpinning the selection of the EMS to be endorsed.

When it comes to the framework itself, there are three main features that signify its novelty: firstly, the detailed reference list of EMS; second, the detailed impact of EMSs, integrating operational features; and finally, in terms of usage, the relationship matrix characterizing the attributes adopted in the framework. In addition, the validation phase of the framework includes an industrial expert's feedback, further to an application of the framework within an energy intensive industry.

In a general sense, the output of the developed framework is more inclusive than existing EM schemes or a mere appraisal of the maturity level, given the meticulous assessment of the EMSs involved in the decision-making process. By considering the framework, industrial organizations have the ability to highlight any significant factors impacting their operational performance, paving the way towards a detailed strategy for EM. It is for this reason that a comprehensive set of EMSs are developed with a defined set of attributes. Such an approach thus allows for the consideration of several important viewpoints to assess EMS adoption, specifically the capabilities and organizational perspectives, and suggest specific actions for each EMS.

The proposed framework also signifies the relevant concerns in EM supply chains within the industrial decision making and policy making process. The framework could be effectively useful in developing EM practices within industrial organizations, adapting to their specific needs. In fact, the framework could be applicable for stakeholders working in the energy efficiency value chain system and wishing to develop their approach to EM. In addition, the proposed framework could also provide support in designing policies towards more effective promotion of industrial EM by acting on a set of articulated attributes.

# Chapter 5

*This chapter investigates the role of Industry 4.0 technologies in terms of improving performance of industrial energy efficiency measures with the impact of production resources and operational performances.*

*This chapter is published in the following conference proceedings and journal:*

*(i) A.S.M.M. Hasan, A. Trianni, "Towards a Framework to Assess the Impact of Industry 4.0 Technologies & Services on Production Resources", IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 07-10 December 2022, Kuala Lumpur, Malaysia DOI: 10.1109/ieem55944.2022.9989725*

*(ii) A. S. M. M. Hasan, A. Trianni, "Boosting the adoption of industrial energy efficiency measures through Industry 4.0 technologies to improve operational performance", Journal of Cleaner Production, vol. 425, p. 138597, Nov. 2023, DOI: 10.1016/J.JCLEPRO.2023.138597*

## 5. Boosting the adoption of industrial energy efficiency measures through Industry 4.0 technologies to improve operational performance

### 5.1 Introduction

Industry accounts for 25% of the global gross domestic product and employment, as well as 42% of the world's electricity consumption [270]. To achieve decarbonization, EEMs are regarded as "first fuel" and crucial for a financially viable energy transition [11]. Energy efficiency (EE) provides a broad set of benefits in multiple areas (e.g. production, work environment, operation and maintenance, waste) beyond just energy savings, known as NEBs [7]–[10]. However, despite numerous claimed benefits of EE, the rate of improvements related to EEMs have slowed down in the recent past [12], contributing to a "energy efficiency gap" [15].

Therefore, looking at "energy" in a broader spectrum within industry is crucial to raise awareness about EE among key industrial decision makers [33], in particular the implications of EEMs on shop floor activities [36]. In fact, assessing the impact of EEMs on production resources and operational performances is of absolute importance in the adoption of industrial EEMs considering the nexus among energy and other production resources (e.g. material, capital, machine, waste) [40].

Simultaneously, the industrial sector is undergoing a technological transformation, which is called the fourth industrial revolution or I4.0 [271]. I4.0 refers to a set of technologies such as cyber physical system (CPS), Internet of Things (IoT), artificial intelligence (AI), big data which are designed to improve the efficiency of industrial systems [46], [272]. I4.0 technologies are claimed to improve the better utilization of industrial production resources, in particular, usage of energy in the upstream and downstream in the industrial value chain [47], [273]. The spectrum of benefits of I4.0 technologies seem to go beyond improved productivity, up to process innovativeness and better collaboration [200], [274], [275].

Studies have started to highlight the implication of I4.0 technologies in terms of sustainability [56]–[58] and technical perspective [59]. Earlier literature featuring I4.0 technologies also have focused on developing algorithms, models, and hardware [48]–[55]. Similarly, research has explored the impact of I4.0 on quality management practices, product and service performance [276]–[278]. However, the existing studies in this area have been lacking sufficient empirical evidence, particularly with regards to the limited focus on industrial EE when examined through the lens of I4.0 technologies. Yet there are very little studies investigating the role of specific I4.0 technologies and how it can best leverage the industrial EEMs to improve operational performance. Furthermore, the scientific understanding about the implications of EEMs on production resources and operational performances has not been established extensively within the industrial context, thus representing a major research gap as detailed in the following section.

Given the initial background, the study aims to assess the contribution of I4.0 technologies in the adoption of EEMs with impact on production resources and operational performances. To support the study, an innovative framework is developed which has been investigated into selected manufacturing enterprises with respect to a subset of I4.0 technologies and EEMs. The research questions of this study are as follows:

- In terms of techno-economic considerations, what are the impacts of EEMs on production resources and operational performances beyond energy and monetary savings?
- What I4.0 technology seems to be the most impactful for the specific EEM? Here, the emphasis on selecting the specific I4.0 technology as not all of the technologies support the adoption of specific EEM.
- What are the production resources and operational performances most affected by the implementation of I4.0 technology in support of the specific EEM adoption?

To the best of author's knowledge, this study is the first attempt to highlight the nexus among I4.0 technologies, EEMs, production resources, and operational performances in the industrial context. In fact, this study presents two distinctive features that contribute to its novelty. Firstly, it provides an empirical investigation into the role of I4.0 in relation to specific EEM, offering valuable insights into their implications on production resources and operational performances. In terms of academic contribution, the proposed framework and the related empirical exploratory investigation aim at addressing a critical gap in the existing literature, towards enhancing an understanding of the potential synergies between the implementation of I4.0 technologies and industrial energy management (EM) at operational level. We argue the framework could be also beneficial to practitioners and industrial decision-makers to unveil the effective contribution of I4.0 technologies with respect to industrial sustainability. More specifically, the framework could help key decision makers in pointing out the EE improvement opportunities within their companies. Furthermore, the developed framework is designed to support decision-makers in better assessing and selecting suitable EEMs, thereby potentially contributing towards the establishment of a robust EM system which is at the very backbone of ISO 50001 certification for businesses [171], [279]. In fact, by utilizing the framework, organizations could more effectively assess different EEMs and select the most suitable based on their overall impact on production resources and operational performance, including improved EE and EM.

### 5.2 Literature background and research gaps

By looking at previous studies on the topic (summarized in Table 20), there are two major streams of literature. On the one hand there is a set of studies more specifically investigating the features of EEMs and their impacts on EE and beyond (e.g., NEBs). On the other hand, other studies are focusing on the contribution of I4.0 to improve industrial operational performance.

The first stream regards a basic attempt to assess impact of industrial EEMs on the production resources [280], [281], limiting the analysis to few cross cutting areas only. Other studies highlight the EEMs' implication at operational performances [282], [283]. However, only few of the operational KPIs are discussed in the studies. The impact of EEMs beyond EE has been investigated by a growing number of scholars. For instance, Skumatz and Dickerson [9], Pye and Mckane [101], Mills and Rosenfeld [103] have argued about the multiple benefits (e.g. improved maintenance, waste reduction) beyond energy savings concerning EE, thus suggesting a link between EE performance and some operational performances. However, a comprehensive view of operational performances is lacking in those studies. Cagno et al. [202] have argued about NEBs in terms of EEMs adoption, nonetheless, too little attention is paid to operational performances inclusively. Similarly, Nehler and Rasmussen [10] have discussed NEBs in terms of EE investment perspective, however the evidence is lacking in terms of operational parameters (i.e. equipment effectiveness, resource utilization) in industries. Other studies have offered a more thorough characterizations of EEM/energy management services (EMS). Fleiter et al. [85] and Trianni et al. [86] attempted to provide a thorough characterization of EEMs to support their adoption in industrial companies. However, such studies have not explicitly explored the connection with other operational performance and production resources. More recently, Hasan et al. [33], whilst contributing to the literature by starting to highlight an EMS characterization with respect to production resources, it is however lacking a thorough perspective over operational performance. Moreover, in such previous studies a clear mention about I4.0 technologies is largely missing.

A second stream focuses at the I4.0 technologies to support operational performance. Here literature is quickly under expansion, with several contributions in EM and optimization strategy. Shrouf and Miragliotta [60] discussed EM in production systems with some mention around IoT. Wang et al. [62] argued about the production performance improvement in smart factory integrating big data based feedback, nonetheless, overlooking the operational performance broadly. On the contrary, Bukataet al. [48], Faheem and Gungor [54] have discussed about energy optimization strategies. However, such studies have not demonstrated the nexus between EE and operational performance metrics. Matsunaga et al. [284] have investigated industrial production processes in smart manufacturing system, however empirical consideration of the production resources and performances are lacking in terms of EE.

Literature has also investigated several technical features (e.g. algorithms, models) of I4.0 technologies [285]–[287] with a broad focus on sustainability. Nonetheless, previous studies have not highlighted the impact of technologies on production performance also including specifically EE. Tortorella et al. [288] have argued about the role of I4.0 in lean manufacturing system, nonetheless little attention is paid to an EE perspective. Tonelli et al. [289] highlighted the methodological perspective to improve operational performance, however the scientific evidence is not conclusive and lacking of elaborate consideration of operational metrics. Similarly, Dalenogare et al. [277] have analysed the potential benefits of I4.0 technologies in terms of operational performances.

The study of the extant works shed light on several complex and intertwined major research gaps, thus supporting current and future research in this area. *First*, EEMs are not comprehensively considered in relation to their impact on production resources other than energy. Considering the correlation amongst energy consumption and production activities in industrial organizations [40], understanding the implications of EEMs on production resources would be crucial for improved decision-making in the operations. In addition, the majority of EEM models seem to emphasize the economic perspective relating to NEBs. This can induce some issues when it comes to understanding the impact of EEMs on an organization’s operations more broadly, i.e., with NEBs extending far beyond an economic performance [202].

*Second*, previous models have not or barely discussed the effect of EEMs on operational performance in an industrial context. Here, integrated strategies that coordinate operational and strategic level concerns with other sustainability metrics are necessary for the efficient implementation of EEMs [36]. In light of this, organizations should assess EEMs operational performance with a focus towards sustainability [198], [199] to obtain a better understanding on operational activities within industrial organizations [36].

*Third*, previous literature specifically on EEMs features has not extensively encompassed the features offered by I4.0 technologies (e.g., production and machine performance observation through real time monitoring using sensors, production planning through the help of simulation tools). I4.0 technologies are claimed to offer increased EE that also positively impact on the production activities [200]. Indeed, there has not been sufficient focus on integrating EEMs and I4.0 from the perspective of industrial operational performance.

*Fourth*, the inclusion of I4.0 technologies in the form of digital control in industrial organizations could bring additional benefits to EEMs, as there might be implications on e.g., asset management through EM and associated services [36], [193]. Unfortunately, the majority of researchers have not explored this research stream to date, and none of them with a specific empirical study.

In a nutshell, the present study builds upon earlier literature streams by investigating the role of I4.0 technologies in boosting the improvement of operational performance by the adoption of EEMs affecting a set of production resources. In order to support the investigation, a new framework has been designed and presented in Section 5.4, encompassing major operational performance, production resources, EEMs and I4.0 technologies.

Table 20. Synopsis of existing frameworks focusing on EEMs and EE features of I4.0 technologies within industrial organizations.

*Legend: ●(Full Consideration); ◐ (Partial Consideration); ◔ (Minor Consideration); ○(Not Considered).

| Authors and year | Study focused area | | | | | | Model Narration | Remark | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | Impact assessment of EEMs on production resource | Impact assessment of EEMs on operational performance | I4.0 into EE | NEB | Characterization of EEM/ EMS | Supports in decision making about EEM | | | |
| Mills and Rosenfeld (1996) | ◔ | ◐ | ○ | ● | ○ | ◔ | Additional benefits of EEMs are discussed in several categories (e.g. indoor environment improvement, reduction of noise) | Industrial EEMs are not specifically considered. | [103] |
| Pye and Mckane (2000) | ◔ | ◐ | ○ | ● | ○ | ◔ | Environmental compliance cost reduction, reduced production costs, improvement of capacity utilization, reliability issues are considered in NEB. | Little discussion about reasoning to the potential benefits beyond energy savings. | [101] |
| Worrell et al. (2003) | ◔ | ◐ | ○ | ● | ○ | ◔ | Economic assessment has been signified; additional benefits are categorized into several categories (e.g. waste reduction, production and quality improvement) | Authors acknowledge the complexity to estimate the magnitude of benefits. | [7] |
| Skumatz and Gardner (2005) | ◔ | ◔ | ○ | ● | ○ | ◔ | NEBs are considered in three categories, which are "Net positive and negative", "Comparison efficiency to standard equipment", and "Net of free riders". | Authors acknowledge the incompleteness of the benefit. | [102] |
| Lung et al. (2005) | ◔ | ◐ | ○ | ● | ○ | ◔ | Focuses on secondary savings and production benefits quantification. | Lack of focus on operational performance. | [87] |
| Fleiter et al. (2012) | ○ | ◔ | ○ | ◐ | ◐ | ◔ | Encompasses technological, comparative advantage, and informative features in NEB. | Energy services are not integrated. | [85] |
| Trianni et al. (2014) | ◔ | ◐ | ○ | ◐ | ● | ◐ | Attributes are characterized into financial, production, environmental, implementation, and interaction category. | Not holistic; Not specific focus on operational performance metrics | [86] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ford and Despeisse (2016) | ○ | ◔ | ◔ | ◔ | ○ | ◔ | Discusses the implications at sustainability concerning from I4.0 technologies, in particular, additive manufacturing are highlighted. | Not holistic; operational performance and production resources are not considered. | [290] |
| Kulatunga et al. (2017) | ○ | ○ | ◔ | ○ | ○ | ◔ | Presents methods for improving energy balance by minimizing energy waste in the industries using algorithm. | EM practices are not integrated in the model. | [285] |
| Nienke et al. (2017) | ○ | ○ | ◔ | ○ | ○ | ◔ | Presents EM 4.0 roadmap integrating the usage of energy data; guided by four maturity levels and integrated by energy consumption data during production. | Lack of focus at EM. | [286] |
| Peralta et al. (2017) | ○ | ◔ | ◔ | ○ | ○ | ○ | EE is discussed in regards of IoT nodes highlighting IoT and fog computing technology in smart factories | Not specific consideration of organizational performance metrics. | [287] |
| Bauerdick et al. (2017) | ○ | ◔ | ◔ | ○ | ○ | ◔ | Highlights the controlling and monitoring of machine at production system based on energy data monitoring. | Not holistic; not specific consideration of operational KPIs. | [291] |
| Junker and Domann (2017) | ○ | ○ | ◑ | ○ | ○ | ◔ | Focuses I4.0 technologies in context to EM; proposes an EM system to collect energy consumption data in the manufacturing industries. | Not holistic; production resources and operational performance are not discussed | [292] |
| Wagner et al. (2017) | ◔ | ◔ | ◑ | ○ | ○ | ○ | Highlights the implications of IoT and services in terms of Lean production system; impact matrix is focused on data acquisition and processing, machine to machine communication, and human machine interaction perspectives | Lack of focus on operational performance indicators and production resources. | [293] |
| Beier et al. (2018) | ○ | ◔ | ◔ | ○ | ○ | ○ | Highlights the implication of IoT on sustainable development attributes (e.g. resource efficiency, sustainable energy, transparency). | Operational performances metrics and production resources implications are lacking. | [294] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| García and García (2019) | ○ | ◔ | ◔ | ○ | ○ | ○ | Discusses the impact of I4.0 technologies at production and maintenance management; 33 production management tasks and 26 maintenance management tasks are considered to show the impact of I4.0 technologies. | Incomprehensive model; lack of consideration at EE and production resource. | [283] |
| Kamble et al. (2020) | ○ | ○ | ◔ | ○ | ○ | ◔ | Investigates the implications of I4.0 technologies and lean manufacturing practices for manufacturing companies in India. | Not comprehensive; little focus on organizational performance metrics. | [295] |
| Ghobakhloo (2020) | ○ | ◔ | ◑ | ◔ | ○ | ◔ | Interpretive Structural Modelling (ISM) is presented to show several relations between I4.0 and sustainability | Insufficient integration of overall operational performance metrics. | [200] |
| Nara et al. (2021) | ○ | ◔ | ◔ | ○ | ○ | ○ | Potential impacts on sustainability are presented concerning I4.0 technologies; model is contextualized based on Brazil's plastic industry. | Lack of consideration at operational performance and production resources. | [282] |
| Cagno et al. (2022) | ◔ | ◔ | ○ | ◔ | ◑ | ◑ | Highlights the impact of EEMs on production resources at shop floor level; attributes are divided into production, social, and environmental categories; | Not comprehensive; operational performance missing; I4.0 features are missing. | [280] |
| Favi et al. (2022) | ○ | ◔ | ◔ | ◔ | ○ | ○ | Uses industrial metabolism concept to focus energy flow; economic factors and sustainability are highlighted at industrial context. | Incomprehensive focus on operational resources and performance. | [296] |
| Tumbajoy et al. (2022) | ○ | ○ | ◔ | ○ | ○ | ◔ | Simulation based assessment in manufacturing process for I4.0 technology; particular focus on overall OEE | Not comprehensive; lack of focus at labour effectiveness and other operational KPIs. | [297] |
| Vogt et al. (2022) | ○ | ○ | ◔ | ○ | ○ | ◔ | Investigate the cyber physical production system to compare performance in heating, ventilation, and air conditioning (HVAC) system at manufacturing unit; four schemes are considered ranging from time based control to model predictive control. | Not specific focus on other cross cutting areas (e.g. electrical motor, compressed air); lack of focus on production resources. | [298] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Hasan et al. (2022) | ● | ◔ | ○ | ◔ | ● | ◑ | Discusses the impact of EMS on production resources at shop floor level; 25 attributes are divided into 4 categories which are implementation, impacted area, production resources, and productivity. | Limited focus on operational performance; I4.0 technologies are not integrated. | [33] |
| Arana-Landín et al. (2023) | ○ | ◔ | ● | ◔ | ○ | ◔ | Discusses the impact of I4.0 technologies on quality management of production process; influence on EE. | Not holistic; limited focus on production performance attributes; NEBs are not considered while considering productivity feature. | [299] |

## 5.3 Research methods

The methodological steps for developing the framework are presented in Figure 12. The initial task in constructing the framework involves identifying the production process and production resources. It is important to note that the selection of production resources is not arbitrary; instead, a meticulous assessment of the enterprise's internal resources is conducted [41], [281]. Likewise, while identifying the operational performances, particular emphasis is placed on the industrial manufacturing context.

The following step entails defining the attributes of the production process, production resources, and operational performances. In this process, we conducted an analysis of pertinent literature from reputable sources such as Scopus and the Web of Science database. Following the attribute definition, the study progresses to the selection of cross-cutting technology areas and the corresponding EEMs. The cross-cutting technology areas are selected based on their extensive adoption and significant energy consumption within industrial sectors. Furthermore, the identification of EEMs relies on the utilization of two databases: the Industrial Assessment Centers (IAC) database of the United States Department of Energy (US DoE) [300], [301] and the Scopus database. The identified EEMs also possess an Assessment Recommendation Code (ARC), which serves as a unique number used within the IAC database. In selecting the EEMs, our emphasis primarily lies in the industrial management perspective within the context of the industrial production processes [86].

The subsequent step in the theoretical development of the framework involves a meticulous identification of the application of I4.0 technologies within the energy domain. This identification process heavily relies on a comprehensive review of relevant literature from Scopus and Web of Science database. By drawing insights from the literature, the framework aims to capture and understand the diverse array of ways in which I4.0 technologies can be applied to enhance EE.

The next step encompasses the validation of the framework with a selected group of industry experts based on their experience in industrial EE activities. The interviewees are carefully selected based on their expertise, particularly focusing on individuals who have a minimum of ten years of experience working in the EE domain at industries. Semi structured interviews are conducted using a predetermined structure and protocol (Appendix A), commencing with a comprehensive overview of the framework to establish effective contextualization. The validation was carried out with 9 experts from November 2022 to January 2023. To this end, previous literature has acknowledged that a sample size of 6–10 could be accepted with a theoretical perspective for the primary validation of exploratory studies [257], [258]. In this study, a qualitative approach was followed to validate the framework whereby semi-structured interviews were used. Each interview lasted for about an hour and have been recorded. Table 21 presents detailed information about the sampled interviewees. The purpose of the interview was to obtain information on the participants' companies, products, and processes as well as their opinions on the framework's inclusiveness, usability, and convenience. Inclusiveness is defined as a group of features to decide whether the categories are clear; attributes are distinct and covering all important metrics. Usability intended to evaluate features for determining the correct labelling of EEMs; valid in helping manage the EEM in accordance with organizational strategy. Lastly, in the convenience section, the ease to use this framework is considered along with its perceived worth to adopt in industrial organizations.

The final step of the study includes the application of the framework in the industries. In doing that, a sample of companies have been chosen to help address the significant variety inherent in the industrial sector. Discussion were carried out according to a pre-defined structure and protocol, starting with a general description of the companies to provide an effective contextualization. To allow for a degree of flexibility in conducting the discussion (see Appendix B for detailed discussion topic), considering the scope of the investigation and the critical effect that specific contexts might have, the semi-structured approach was adopted [148], [256].

In this application phase, information regarding the relevance of I4.0 technologies and EEMs were asked, also in terms of EEMs previously implemented. Furthermore, the roles of I4.0 technologies to boost the performance of EEMs are discussed thoroughly, as different subset of I4.0 may impact differently with respect to EEM. Besides, the impact of production resources and operational performances stemming from I4.0 with respect to EEMs are carried out.

Table 21. Data of the interviewed experts and their organizations

| ID | Designation | Job description | Experience of interviewee in EE field (years) | Activities of concern organization | EM status in firm | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Dedicated Energy Manager (Yes/No) | EM policy (long term/ short term) | Energy Audit Conduction (6 months/yearly/more than one year interval) | EM training for staff (Yes/No) |
| C1 | Senior Advisor (resource management) | Supervision of EE programs | 13 | Water treatment | Yes | Short term | Yearly | Yes |
| C2 | Chief Technical officer | Supervision of EE programs | 30 | Energy solution provider | No | Short term | Not applicable | No |
| C3 | Chief Technical officer | Supervision of operation management | 17 | Apparel manufacturer | Yes | Long term | Yearly | Yes |
| C4 | Specialist (energy productivity) | Engage in EM programs | 10+ | Industrial production management | No | Short term | Yearly | Yes |
| C5 | General Manager | Engage in driving solutions, digital innovation and enterprise transformation in energy sector. | 10+ | Energy services provider | Yes | Long term | Yearly | Yes |
| C6 | Managing Director | Involved in EM programs; energy advice | 12+ | Energy services provider | No | Short term | Yearly | Yes |
| C7 | Senior Manager | Supervision of production management | 15+ | Apparel manufacturer | No | Short term | Yearly | Yes |
| C8 | Deputy Manager | Responsible for production management, involved in EM programs | 12+ | Consumer goods manufacturer | Yes | Long term and short term | Yearly | Yes |
| C9 | Assistant manager | Responsible for production management. | 10 | Steel manufacturer | Yes | Long term and short term | Yearly | Yes |

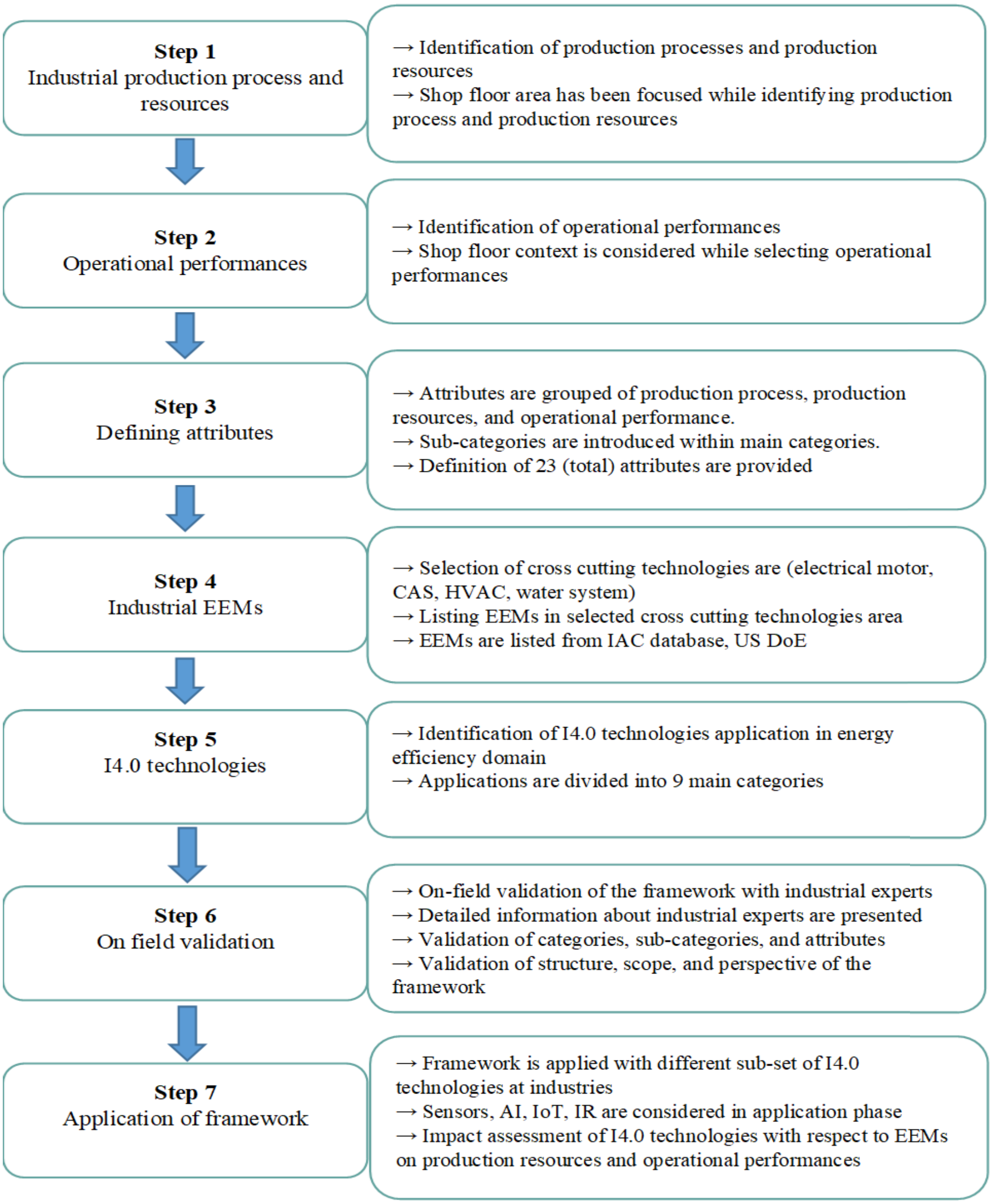


Figure 12. Flow chart of methodological steps

## 5.4 Novel framework encompassing EEM to production resources and operational performance

The detailed description of the attributes upon which the framework is designed is presented in the following section. As a foundation, we have taking inspiration by previous studies of Fleiter et al. [85] and Trianni et al. [86] to select and describe the attributes. Here, the attributes are not selected randomly, rather we adhered with the learnings from knowledge representation science [201] for the characterization exercise. For example, the categories were proposed with the aim of characterizing any

EEM based on a broad range of attributes. Following similar approaches in literature [85], [86] we have considered the perspective of key industrial decision maker's in implementing any EEM. In fact, to assess the EEM properly, industrial decision makers require adequate details on several attributes including energy, economic, environmental, machine and labour effectiveness, productivity, and others. The attributes in this framework are divided into three categories: operational performance, production resources, and production processes. The categories are further grouped into subcategories. This framework integrates categories by combining simple attributes that are neither brief nor extensive. Additionally, emphasis was given to reduce the overlap among the different groups.

### *5.4.1 Production process*

To adequately support key decision-makers in their evaluation of EEMs, it is important to identify the affected areas in industrial production processes. In this framework, by taking inspiration from Fleiter et al. [85], two major areas are considered to show the implications of EEMs, namely the (i) *core technical process* and (ii) *auxiliary processes*.

### *5.4.2 Production resources*

Production resources can be categorized in diverse ways. For example, capabilities, assets, knowledge, information, processes, stocks, and trust are frequently mentioned by organization theorists [302]. On the other hand, economists emphasize factors of production, including land, labour, capital, knowledge, ideas, capabilities, and skills [303]. Similarly, accountants focus on information, materials, and machines [212]. However, a notable distinction is the classification of resources as intangible (such as knowledge) or tangible (such as capital), as well as transformational (like energy) or transformed (such as raw materials) [41]. In this study, production resources are defined as internal to the firm and possessing a tangible nature. This selection is guided by the practicality of identifying and managing resources that can be easily identified. Moreover, this conceptualization establishes a solid foundation for evaluating the implications of EEMs in the manufacturing enterprises.

EEMs have a substantial impact on industrial production processes [40], necessitating a more thorough explanation of their connections [61]. Taking inspiration from earlier studies, the impact of production resources due to EEMs are divided into 7 sub-categories in this framework: *(i)* machinery [40], *(ii)* capital [208], *(iii)* energy [208]–[210], *(iv)* utilities and building [211], *(v)* human resources [212], *(vi)* materials and resources [40], [208] and *(vii)* waste [40], [208]. Table 22 presents a thorough description of attributes with a focus on production resources.

### *5.4.3 Operational performance*

Operational performance is a key and well-known indicator of industrial production process efficiency. In manufacturing organizations, operational performance is an important consideration, given its impact on bringing effectiveness in production, quality, customer satisfaction, and increasing revenue [304], [305]. Bayraktar et al. [306] argued that, to measure operational performance, several attributes are necessary. Therefore, researchers have encompassed several indicators to measure operational performance. For example, Corbett and Van Wassenhove [307] focussed on cost, quality, and delivery time to express operational performance. In contrast, Samson and Terziovski [308] focused on "productivity", "quality", and "performance" to express operational performance. Similarly, Jabbour et al. [309] and Slack [310] included quality, cost, flexibility, delivery, and production speed to measure operational performance in companies. On the other hand, Jacobs and Chase [311] incorporated operation time (combination of setup time and runtime), production speed/velocity, throughput rate, efficiency, productivity, and utilization to characterize operational performance. However, in this framework we have tried to emphasize machine effectiveness and labour effectiveness inclusively. Therefore, two distinct attributes are encompassed, namely *overall equipment effectiveness* (OEE) and *labour effectiveness* to show detailed performance metrics. Notably, OEE [312], [313] and labour effectiveness [314] as distinct KPIs are largely diffusing in industries to show operational performance with greater detail.

Detailed descriptions of attributes grouped into division and sub-division, focusing on operational performance are presented in Table 22.

Table 22. Defined attributes of production resources and operational performances

| Division | Sub-division | | Remark |
|---|---|---|---|
| Production resources | Machine | | Refers to any device that run by electrical, mechanical, or chemical energy at industrial environment [7], [8], [10]. |
| | Capital | | Financial resources available for use in the industrial processes [45]. |
| | Energy | | Refers to energy forms (i.e. electricity). |
| | Utilities & building | | This attribute includes the physical arrangement of industrial facilities and HVAC system [218]. |
| | Human resources | | Manpower working at the organization [219]. |
| | Material & resources | | Input goods/ inventory that are used for production in the industries. |
| | Waste & emission | | Emissions and industrial waste (hazardous and non-hazardous) which are produced during industrial activity. |
| Operational Performance | Overall Equipment Effectiveness | Availability | The proportion between the equipment's actual operation time and its total scheduled operation time [220]. |
| | | Performance | Refers to how well the equipment are working as designed for industrial activity [315]. |
| | | Quality | Ratio of production at desired condition and total produced goods in the industrial context [316]. |
| | Labour Effectiveness | Performance | Ratio of actual productive working time and scheduled working time of the human workforce [314]. |
| | | Quality | Ratio of labour input divided by man-hours [317]. |
| | Operation Time | Setup time | Required time for preparing the manufacturing processes & system for production [318]. |
| | | Run time | The actual operating time for producing output in the industrial system. It is calculated by subtracting setup time & downtime from planned production time [318]. |
| | Throughput | | Rate of production in industries over a predetermined period of time is referred to as "throughput" [222]. |
| | Productivity | Resource utilization | Refers to how production resources are managed and how well they are used across the many stages of industrial operation. |
| | | Efficiency | Ratio of actual production in standard hours and actual production time [311], [319]. |
| | Reliability | | Refers to a system whether it can perform correctly as designed in a defined environment [7]. |
| | Flexibility | | How operation responds to any external issues (e.g. change in supply demand, disruption in machine) [310], [320]. |
| | Production speed | | Ratio of flow time and value added time in industrial system [311]. |
| | Operational cost | | Ongoing expenditure (e.g. equipment running cost, inventory cost) for regular activities in the industries [319], [321]. |

## 5.4 EEMs and Industry 4.0 technologies for energy efficiency

### 5.4.1 Selected cross cutting technologies

The presented framework can be applicable for any suitable EEM. Nonetheless, for the application four cross cutting technologies have been considered (i.e. electrical motors, compressed air system and HVAC and water systems), based on their wide diffusion and the fact they present major areas of energy consumption in industrial production processes [86].

Within cross cutting technologies, **electrical motor systems** are responsible for two thirds of industrial power consumption, given their broader range of applications [322], [323]. In fact, electrical motors account for 30-80% of industrial energy globally [324]. Generally, an electrical motor is efficient with a rating above 80%. However, with the adoption of best-practice EEMs, savings of 11-18% could be obtained [322].

The usage of **compressed air** is largely applied in industrial manufacturing processes and accounting of a relevance share of energy consumption in various contexts [325]. Nonetheless, the efficiency of compressed air systems is often quite low and studies [86], [230] show that compressed air driven tools utilize 10–15% of the energy input. Though, with the help of EEMs, about 56% of savings could be achieved for compressed air systems [326].

The **Heating, ventilation, and air conditioning** *(*HVAC) system has a considerable share on energy consumption within industrial production processes. More importantly, HVAC systems do not only have implications on production processes, rather also providing a comfortable environment within industrial premises. In buildings, HVAC systems are accountable for about 50% of total energy consumption [217]. Nonetheless, with the help of adequate EEMs, 40% of energy could be saved within a HVAC system [327], [328].

Finally, the significance of the **water system** in industrial processes can be appreciated considering the nexus between energy, water and production activities. Though, although the impact of pumping systems on industrial water systems is apparent, little research has explicitly looked at EEMs within water systems in industry. Studies have started to mention a better utilization and management of resources in industrial organizations stemming from the adoption of EEMs in water system [261], however lacking a thorough empirical evidence.

### 5.4.2 EEMs identification in selected cross cutting technologies

Extant literature has widely discussed EEMs in terms of industrial applications, commercial buildings, hospitals and others. However, little work has been done towards specifically assessing industrial EEMs with respect to operational performance and production resources. Therefore, we have considered a total of 13 EEMs under four main cross-cutting technologies along with the application presented as Table 23. The EEMs have been identified based on Scopus and Web of Science indexed journals, reports and technical notes by the US Department of Energy [300], [301]. In doing this, we mainly emphasized the industrial management perspective within industrial production process [86].

By taking inspiration from earlier studies [26], [86] this was performed by using data from literature that discussed some of the characteristics of EEMs and how they relate to the effects on production resources and operational performance. This is to acknowledge that the list does not encompass EEMs in detail. Nonetheless, it was believed to be large enough for a broader overview of EEM features. Of course, the framework is designed to understand EEMs and their implications on production resources and operational performance holistically. Therefore, we attempt to present a set of valuable perspectives to characterize EEMs. However, the actual impacts on operational performance may differ for a particular application of EEM within a company based on industrial sector, firm size, and the nature of energy consumption. Therefore, more tailored and detailed information are required to consider EEMs and their implications on specific production resources for accurate decision-making processes.

Table 23. The framework incorporating industrial EEMs, production resources and operational performance

| Area | ARC | Energy Efficiency Measure | Reference | Category | **Production process** | | **Production resources** | | | | | | | **Operational Performance** | | | | | | | | | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Core technical process | Ancillary process | Machine | Capital | Energy | Utilities & building | Human resources | Material & resources | Waste & emission | Overall Equipment Effectiveness | | | Labour Effectiveness | | Operation Time | | Throughput | Productivity | | Reliability | Flexibility | Production speed | Operational cost | |
| | | | | | | | | | | | | | | Availability | Performance | Quality | Performance | Quality | Setup time | Run time | | Resource utilization | Efficiency | | | | | |
| EMS | *2.4 111* | *Utilize energy efficient belts* | [329], [330] | O | H | M | H | M | H | N/A | M | L | M | P/ N* | P* | P* | P/ N* | P/ N | P* | P | P | P | P* | P | P* | P | D | [67], [322], [323] |
| EMS | 2.4 112 | Installation of soft start | [330], [331] | O | L | L | H | L | M | N/A | M | L | N/A | P* | P | P | P | N/A | P* | P | P | P | P* | P | P | P* | D | [323], [332] |
| EMS | *2.4 146* | *Usage of adjustable frequency drive or multiple speed motors on existing systems* | [64], [330], [331], [333], [334], [322] | MSD | H | M | M | M | H | N/A | M | L | M* | P* | P* | P | P | P | P | P | P | P | P* | P | P | N/A | D | [322], [335], [336] |
| EMS | *2.4 154* | *Avoid rewinding motors more than twice* | [64], [330]–[332] | M/R | L | L | H* | L | L | N/A | H | L | N/A | P* | P* | N/A | P | N/A | N/A | P | P | P | P | P | P | N/A | D | [64], [331] |
| CA | *2.4 224* | *Upgradation of control mechanism for compressor* | [301], [337]–[339] | HW | L | L | H | M | M | Y | H | M | L | P | P* | P | P | P | P | P | P* | P | P* | P | P | P* | D | [333], [340] |
| CA | *2.4 235* | *Removal of unneeded compressed air line* | [301], [341], [342] | O | M | L | N/A | M | M | Y | L | L | L | N/A | P | P | P | N/A | P | P | P | P* | P | P | P | P | D* | [342], [343] |
| CA | *2.4 236* | *Elimination of leaks in air line* | [301], [333], [337] | O | H* | M | N/A | H | H* | N/A | L | M | M | N/A | P* | P | P | N/A | P | P | P* | P* | P* | P | P | P | D* | [342], [343] |
| HVAC | *2.7 226* | *Usage of Computer aided programs for optimizing performance* | [64], [301], [333], [344], [345] | O | L | L | L | L | M | Y | M | L | L | P | P | N/A | P | N/A | P | P | P | P | P | P | P | P* | D | [345] |
| HVAC | *2.7 234* | *Usage of heat pump for space conditioning* | [301] | HW | L | L | L | M | H* | Y | L | L | L | P | N/A | N/A | N/A | N/A | N/A | P | N/A | N/A | P | P | P | P | N/A | |
| HVAC | *2.7 243* | *Air circulation improvement with destratification fans or other methods* | [301], [333], [346] | HW | L | L | L | L | M | Y | H* | M | N/A | P | P | N/A | P | N/A | N/A | P | N/A | P* | P | P | P | P* | N/A | [333], [346], [347] |
| W | *3.4 111* | *Usage of closed cycle process to minimize waste water production* | [301], [348] | CC | M | M | L | M | M | N/A | L | M | M | P | P | N/A | N/A | N/A | P | P | P | P* | N/A | P | P | P | D | [349] |
| W | *3.4 154* | *Elimination of leaks in water lines & valves* | [12], [351], [38] | RD | L | L | N/A | L | M | N/A | L | H | H | P | P | P | P | N/A | P | P | P | P* | P | P | P | P* | D | [351] |
| W | *3.4 155* | *Sub-metering/ quantification of water usage* | [301], [349], [352], [353] | RD | L | N/A | N/A | L | L | N/A | L | M | M | P | N/A | N/A | P | N/A | N/A | N/A | N/A | P | P | P | N/A | N/A | D | |

In the framework, the asterisk (*) refers to the literature backup.

(1) Electrical Motor Systems (EMS); Compressed Air (CA); Heating-Ventilation-Air Conditioning (HVAC); Water (W)
(2) Operation (O); Hardware (HD); Motor System Drive (MSD); Maintenance/Repair (M/R); Closed Cycle Water Usage (CC); Reduction (RD)
(3) High (H); Medium (M); Low (L); Not-available (N/A).
(7) Yes (Y); No (N); Not-available (N/A).
(8) Strongly positive (SP); Positive (P); Negative (N); Not-available (N/A)

### 5.4.3 I4.0 technologies for energy efficiency

The foundation of I4.0 has been laid by the advanced automation system (e.g. robotics, smart sensors) as well as set of information technology and communication networks (e.g. Internet of Things, artificial intelligence, machine learning) consisting of data collection and analyzing system [354], [355]. A short description about various I4.0 technologies is presented in Table 24.

Table 24. Short summary of selected I4.0 technologies

| Technologies | Description |
|---|---|
| CPS | Connect physical and computational process in order to monitor system. |
| IoT | Industrial ecosystem that integrates intelligent machines with autonomous functionality, advanced analytical features with predictable nature, and human-machine interaction [356]. |
| Big data | Technologies that collect as well as analyze large volume of data. |
| Cloud technology | Virtual storage system for programs, applications, and data. |
| AI | System that involves creating machines capable of performing tasks based on knowledge presentation, natural language processing, machine learning, data driven reasoning, computer vision and robotics. |
| Simulation and modelling | Technologies that replicate the real-world process and systems virtually |
| Visualization technology | Augmented Reality: a set of technology that superimposes Human Computer Interaction (HCI) techniques, allowing users allowing users to interact with virtual objects in real-time.<br>Virtual Reality: application of technology to create an interactive world through the use of computer-generated visuals and sounds, allowing users to interact with virtual objects in real-time. |
| Automation and industrial robots | Machinery and equipment that computerize operational procedures; allows humans and machines to function collectively |
| Additive manufacturing | Process of joining materials in successive layers to make objects from 3D model data |
| Block-chain | A digital ledger technology that records transactions across a network of computers and ensures that the data stored within it is secure, transparent, and immutable. |

One of the salient features of I4.0 is the better decision making process due to its interconnected advanced and intelligent machines [104]. The deployment of smart machinery offers diverse benefits which primarily includes manufacturing productivity and waste reduction. In addition, it enhances the efficiency and overall productivity of the production resources [357].

In the domain of Industry 4.0 and energy management, literature has highlighted the technical parameters (e.g. vertical integration, virtualization, flexibility, automation, and traceability), in particular, interconnection of technical parameters. In fact, studies have highlighted three aspects in energy, which are (i) predict, monitor, and management (ii) strategies to improve efficiency (iii) technology innovation [273], [358]. Table 25 presents the application of I4.0 in energy domain. In developing the Table 25, we have considered cyber physical system and AI considering their wide spread application in the industrial energy management. Being said that, any I4.0 technology is applicable for the attributes presented in Table 25.

# Table 25. Applications of I4.0 in energy efficiency domain

| Industry 4.0 | | Applied methods to enhance energy productivity | Description | Application of Industry 4.0 into energy domain | | | | | | | | | | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | System design | | Efficiency | Forecasting | | Metering & monitoring | | Benchmarking | Management | | | | Energy harvesting | Energy data visualisation | Reporting | |
| Major technologies | Technology components | | | Energy supply chain network | Energy system | | Energy consumption | Energy performance | Energy consumption | Energy performance | | Allocation | Scheduling | Control & optimization | Collaboration with other production resources | | | | |
| Cyber-physical systems | Distributed control system; actuators; sensor networks | Data monitoring and acquisition | Process of review, evaluation, and digitization of data from the system. | M | H | P | Y | Y | Y | Y | P | M | M | H | H | N/A | Y | Y | |
| | | Value stream mapping | Method of acquiring data of applied energy in each process | H | M* | SP | Y | Y* | Y | Y | SP | H* | H | N/A | M* | N/A | N/A | N/A | [207] |
| | | Real time control | Control of energy flow & machine status over time | H | H* | P* | N/A | N/A | Y* | Y* | P | H | H | H | H | N/A | N/A | N/A | [46], [359]–[361] |
| AI | Algorithms; optimization techniques | Optimization algorithms | Manage and control WSN communications and functionality | N/A | M | P* | N/A | N/A | N/A | M | P | N/A | N/A | M | N/A | Y | N/A | N/A | [54] |
| | | NSGA-II & NRGA evolutionary algorithms | Algorithms to balance and schedule of loads based on energy | N/A | H | P | N/A | N/A | N/A | N/A | P | M | H | M | N/A | Y | N/A | N/A | |
| | | Energy-aware load balancing and scheduling | Apply fog nodes to analyse energy consumption; achieving load balance & scheduling | N/A | H* | SP | N/A | N/A | N/A | N/A | P | H | H* | H | M* | Y | N/A | N/A | [362] |
| | | Evolutionary algorithms | Algorithm to solve single-objective manufacturing scheduling problems by energy awareness | N/A | H | SP | Y | Y | N/A | N/A | N/A | M | H | H | M | Y | N/A | N/A | |
| | | Ant colony optimization algorithm | Algorithm that reduces the weighted energy consumption | N/A | M | SP | Y | Y | N/A | N/A | P | H | H | H | H | Y | N/A | N/A | |
| | | Genetic algorithm | Algorithm that optimize energy cost in the unit process by creating a set of jobs | N/A | H* | SP | Y | Y | Y | Y | P | H | H* | H* | H | N/A | Y | N/A | [363] |
| | | Particle swarm optimization | Focuses on task-related priorities to achieve the optimized solution in manufacturing clusters | N/A | H | SP | Y | Y | N/A | Y | P | H | H | H | M | Y | N/A | N/A | |
| | | Branch & bound algorithms | Focuses on energy consumption minimization by applying power-saving modes and energy-efficient order of tasks | N/A | H* | P | Y | Y* | N/A | N/A | P | H | H | H* | M | N/A | N/A | N/A | [48], [364], [365] |

Asterisk (*) refers to the literature backup.
(1) High (H); Medium (M); Low (L); Not-available (N/A).
(2) Yes (Y); No (N); Not-available (N/A).
(3) Strongly positive (SP); Positive (P); Negative (N); Not-available (N/A)

### 5.5 Validation and application of the framework

#### 5.5.1 On-field validation

As presented in Table 26, interviewees identified no significant overlap in the categorization of attributes with regard to validation. In fact, the framework received very positive comments from every interviewee. Moreover, the interviewees made it very evident that they understood the value of evaluating EEMs. In conclusion, the model is acknowledged by the interviewees for both its approach and potential for adoption in industrial organizations.

Table 26. On-field validation result

| ID | Inclusiveness | | Usability | | | Convenience | |
|---|---|---|---|---|---|---|---|
| | Category | Attributes | Labelling | Application | Valid & prompt help | Easiness to use | Adoption |
| C1 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| C2 | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| C3 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| C4 | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓✓ | ✓✓ |
| C5 | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓✓ | ✓✓ |
| C6 | ✓✓ | ✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| C7 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓✓ |
| C8 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| C9 | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓✓ |
| Key comments about the framework | *"The framework helped to identify the impacts of EE which are not taken into consideration in decision making phase"* | | *"The framework has brought a new perspective to look at operational performance through EE; previously the impacts of EE were overlooked; useful framework to assess the EEM and digital technologies"* | | | *"Broader knowledge over operational performance is certainly helpful, however was not available before"* | |
| Further suggestion | Sub-categorization of EEMs should be included. | | Proposed mixed impact (positive & negative) in the mapping matrix | | | | |

*Legend: ✓✓(Positively evaluated); ✓ (Positively evaluated with further suggestions proposed); ✗ (Negatively evaluated).

#### 5.5.2 Case Studies within industrial companies

The application of the framework for the selected industrial companies is thereinafter presented. The application is crucial to understand the framework applicability across multiple industries. Three different industrial organizations are considered for the application, referring to crucial sectors in the manufacturing sector such as (i) electronic appliances, (ii) textiles, and (iii) food and beverage. Within the exploratory nature of the present investigation, energy consumption represented a key factor in sampling industries. Textile and electronic manufacturing company are both energy intensive industries. Whilst in electronics significant electricity consumption can be noted, in textile industry a large amount of energy is primarily used for raw material processing, dyeing & printing, finishing process, and HVAC [366]. The food and beverage industry also has several units that consumes a large amount energy, primarily due to the large use of heat within the production processes.

While applying the framework, the noteworthy EEMs and I4.0 technologies are discussed together with further details emerged in the discussion, leading to a comprehensive mapping matrix encompassing impact of EEMs and I4.0 technologies. Ultimately, the framework has allowed a holistic assessment of EEMs with a clearer understanding of the effective role of specific I4.0 technologies in boosting specific operational performance affected by the adoption of selected EEMs.

#### 5.5.2.1 Company A: Electronic appliance manufacturer

The participating company is ISO 9001 and ISO 14001 certified. The company is located at Bangladesh and has been operating since 1972. The mill has the capacity to produce annually 72 million electronic appliances that include refrigerator, compressor, television, and washing machine. The annual turnover is 803 million USD. Electricity is the primary energy source in the plant; annual energy consumption is 365 GWh. Process energy, HVAC, and water are the main sectors that consumes the large portion of energy. The company has implemented several energy efficiency measures in electrical motor system, compressed air, HVAC, and water system. However, for the purpose of this study only four energy efficiency measures are considered for the discussion.

One of the considered EEMs is "*usage of AFD adjustable frequency drive (ARC 2.4146)"* in electrical motor system. In this manufacturing plant, AFD is used in the conveyer belt system, pump & blowers unit, and compressor unit. While applying the framework for ARC 2.4146, we have observed that "machine" and "energy" are the impacted production resource. In addition, overall equipment effectiveness and reliability is also improved. For example, utilizing AFD is helping to reduce the wear & tear on electrical motor by a soft start and stop, which has resulted stress reduction of the motor and associated equipment in the plant. These features have helped to reduce the frequency of machine breakdowns and repairs, leading to downtime reduction. Furthermore, the plant manager acknowledged improved precision and accuracy of electrical motor by providing greater control of their speed and torque.

The plant has also installed dryer (*ARC 2.4222*) to remove moisture in the CAS. Moisture can cause corrosion which leads to equipment damage and efficiency reduction of the system, and can also cause problems with certain processes that require dry air. Installation of dryer thus have impact on machine and improves the OEE significantly. Similarly, the usage of computer aided program (*ARC 2.7226*) in HVAC significantly improves reliability, and decrease waste thus leading to reduced operation cost. Again, when it comes to closed cycle process in water system (*ARC 3.4111*), it has significant impact "material & resources". In fact, the plant manager has acknowledged a significant reduction in water requirement demand in the production process due to the reuse of desalinated water. The operational cost was also reduced to 2-3% stemming from the reduced demand of desalinated water.

However, when asked about further boosting the operational performance by I4.0 technologies, smart sensors and artificial intelligence (see Table 27) seem to improve more thoroughly the operational performance with real time monitoring and controlling of machine temperature, pressure, flow, and vibration. For instance, while using AFD in EMS, sensors help to monitor the current flowing through the motor and further adjust the frequency of the electrical power supplied to motor. Additionally, the vibration and temperature can also be precisely monitored. Nonetheless, with the help of AI, the OEE can be much more improved. In fact, AI analyse the real time data of motor speed, current, temperature in order to determine if maintenance is required, thus leading to prevent unplanned downtime in the plant, increased reliability and flexibility [367]. Moreover, AI helped to optimize energy consumption in the plant by adjusting the frequency of electrical power supplied to the motor, thus leading to reduction of operational cost [368].

Similarly, AI is equally creating positive impact for computer aided programs in HVAC system and usage of closed cycle process in the water system. For example, AI-based algorithms are used to analyze data from sensors to detect and diagnose faults in HVAC system, control the temperature and airflow in the shop floor based on the time of day, weather, and occupancy. Again, considering water system, the similar features are equally applicable. Such features significantly optimize the operation of the HVAC system to reduce energy consumption and improves the OEE, OLE, system reliability, and reduce operation cost. In fact, with the help of sensors and AI platform, the manufacturing plant has saved 5% of water and other materials consumption compared to the previous years. On the other hand, by looking at industrial robots (see Table 27), it has impact on material and resources for the EEMs, however, not creating significant implication compared to sensors and AI.

Table 27. Impact of I4.0 technologies on EEMs with the consideration of production resources and operational performances at Company A (electronic appliance manufacturer)

| I4.0 technology | Cross Cutting Area | Energy Efficiency Measure | Production Resources | | | | | | | Operational Performance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Machine | Capital | Energy | Utilities and building | Human resources | Material and resources | Waste and emission | OEE | OLE | Operation Time | Throughput | Reliability | Productivity | Flexibility | Production speed | Operational cost |
| Sensor | EMS | Usage of adjustable frequency drive | M / H | | M / N.O. | | | | | +/++ | | | | +/ ++ | | +/ × | | +/ × |
| | CA | Installation of dryers at air-line | M / H | | | | | | | +/++ | | | | +/ × | | | | |
| | HVAC | Usage of Computer aided programs | | | M / N.O. | M / H | | | M / H | +/++ | +/++ | | | +/++ | | | | +/ ++ |
| | W | Usage of closed cycle process in water | | | | | | M / H | M / N.O. | | | | | | +/++ | +/ × | | +/ ++ |
| AI | EMS | Usage of adjustable frequency drive | M / H | | M / H | | | | | +/ +++ | | | | +/ ++ | | +/ ++ | | +/ ++ |
| | CA | Installation of dryers at air line | M / H | | | | | | | +/ +++ | | | | +/ ++ | | | | |
| | HVAC | Usage of Computer aided programs | | | M / H | M / H | | | M / H | +/ +++ | +/ +++ | | | +/ ++ | | | | +/ ++ |
| | W | Usage of closed cycle process in water | | | | | | M / H | M / H | | | | | | +/++ | +/ ++ | | +/ +++ |
| IR | EMS | Usage of adjustable frequency drive | M / H | | M / N.O. | | | | | +/ ++ | | | | +/ × | | +/ × | | +/ × |
| | CA | Installation of dryers at air line | M / H | | | | | | | +/ ++ | | | | +/ ++ | | | | |
| | HVAC | Usage of Computer aided programs | | | M / N.O. | M / H | | | M / N.O. | +/ × | +/ × | | | +/ × | | | | +/ × |
| | W | Usage of closed cycle process in water | | | | | | M / N.O. | M / N.O. | | | | | | +/ × | +/ × | | +/ × |

Note: In the impact matrix, first part shows the impact of EEM without considering I4.0 technology, second part shows the impact of EEM with the integration of specific I4.0 technology

(1) High (H); Medium (M); Low (L); Not-observed (N.O).

(2) Strongly positive (+++); Positive (++); Mildly positive (+); Negative (-); Not observed (×)

#### 5.5.2.2 Company B: Textile & apparel manufacturer

The textile and apparel manufacturing firm has been in operation since 1982 in Bangladesh, producing outdoor and athletic clothing, textiles, footwear, and gear, with an annual turnover of 2.21 Billion USD. The primary energy source used in the plant is electricity, with an annual consumption of 305 GWh. The textile plant has spinning, weaving and/or knitting, and wet processing that includes preparation, dyeing and/or printing, and finishing section. Spinning demands the greatest share of electricity (40%) followed by weaving (19%). The other energy consuming activities include wet-processing preparation, dyeing and printing, and finishing.

As a part of the EM system, the plant avoids rewinding motors more than twice (*ARC 2.415*4). It is common practice to rewind a motor after failure in motor windings [369]. However, rewinding can lead to a decrease in efficiency [324]. Therefore, it is found economically convenient to replace a motor below 20 hp with a new high efficiency motor, instead of rewinding it [324], [370]. While implementing ARC 2.4154 (see Table 28), "machine" is observed as critical consideration within production resource. By avoiding rewinding motors more than twice, a significant improvement in machine effectiveness is observed, as well as reduced maintenance compared to motors that have been rewound multiple times.

Similarly, the use of air filter (*ARC 2.4227*) in CAS is applied in the plant (see Table 5) which is crucial for removal of contaminants (i.e. particulates, condensate, and lubricant). Different types of air filters are used based on the level of air purity required in the system [342]. While applying this EEM, we have observed a critical implication, particularly on the "machine". Again, while looking at the operational performances, a strong positive impact on equipment effectiveness, particularly on machine performance and quality was observed. It seems logical as the filter protects the machine from unexpected dust and contaminants, which is crucial for machine performance [371], [372]. Further, the operation cost is also minimized due to less equipment maintenance.

This textile industry has a considerable water consumption. Optimizing the water consumption is very important, being water a scarce and precious commodity. Utilizing optimization techniques in water system holds utmost significance considering resource utilization and sustainability perspective [373] in an industrial context. The investigated plant uses flow control valves to optimize water consumption (*ARC 3.4156*) in the production process. Whilst applying the EEM, it is observed that material and resources are significantly impacted (see Table 28). In fact, by controlling the water flow better utilization of resources are acknowledged by the plant manager.

Again, when asked to boost the operational performances further for the applied EEMs with the help of Industry 4.0 technologies, IoT and AI seem to have critical implications. Interestingly, in one of the new production units, IoT technologies have allowed to avoid rewinding of motors more than twice by monitoring the real-time operational performance of the motor through the use of smart sensors. The sensors monitor the current flowing through the motor, temperature, pressure, flow, and vibration and send the data to the AI system for further analysis. The AI system then uses this data to determine if maintenance is required and can take action to prevent unplanned downtime in the plant, increase overall equipment effectiveness, reliability, flexibility, and optimize energy consumption (see Table 28). In fact, we can appreciate the significant improvement (from mildly positive (+) to strongly positive (+++)) in OEE, flexibility, and reliability with the help of AI.

Similarly, AI significantly improves CAS system performance in the plant. As mentioned earlier that the plant uses filter in CAS to remove contaminants. Generally, by using a filter, some air pressure drops in the system may negatively affect productivity. However, AI is used to analyse the real time data of the system and determining the optimal conditions for the air filter to operate efficiently. In addition, AI based platform monitors the pressure, flow rate, and other relevant parameters in the CAS and use this information to determine the most efficient operating conditions for the filter, when cleaning or replacement are needed. Additionally, AI based platform is also helping to optimize energy consumption in the CAS by adjusting the air flow rate and pressure as needed. All these features are inclusively impacting to improve reliability (see Table 6); from mildly positive (+) to strongly positive (+++)). Additionally, the operational cost has been reduced thanks to reduced energy consumption (see Table 28).

#### 5.5.2.3 Company C: Food processing company

The food processing plant located in Australia processes various food items including vegetables, meat, and rice, employs 436 workers and presents an annual revenue of 52.3 million USD. The energy consumption of the plant is estimated to be 63 GWh per year. The main energy-consuming units in the plant include refrigeration, heating and cooling systems, processing equipment such as mixers and grinders, lighting, and compressed air systems.

One of the EEMs applied in the plant is energy efficient belt utilization (*ARC 2.4111*) in electrical motor system. Literature have discussed several EEMs relating to the "*utilization of energy efficiency belts and improved mechanism[s]*" which include the use of either synchronous, flat, or cogged belts, or other mechanisms as high frequency gears, direct coupling motor and drive, etc. [322], [323]. Whilst applying the framework for ARC 2.4111 (synchronous belts), we have observed that machine, and energy are critically considered as production resources (see Table 29). Again, due to the implementation of the EEM, the overall effectiveness of equipment is significantly improved (see Table 29). However, additional retrofitting was required, and the volume of maintenance work also increased, resulting in additional worktime. In addition, whilst looking at the other operational performance metrics, we have observed a positive impact on production speed and reliability in operational processes.

Similarly, as a part of EM system, the plant does the cleaning and maintenance of refrigerant condenser and towers (*ARC 2.7211*) on a regular basis. Here, IoT technology such as smart thermostat, sensors, and actuators are integrated in the HVAC system in the plant since mid of year 2022. In the participant plant, IoT-enabled sensors are used to check and monitor the performance of condenser and tower by looking at the debris and dirt build-up as well checking for any signs of corrosion or damage. The maintenance team further uses the sensor's data to take measures about cleaning of HVAC equipment. The regular cleaning of HVAC systems has provided more consistent and reliable temperature and humidity control in the shop floor. This has reduced the risk of respiratory problems among workers, leading to a healthier and improved labour effectiveness (see Table 29; mildly positive (+) to positive (++)). Interestingly, the plant manager acknowledged an improvement of working conditions, measured through a reduction of sick leave applications in the last quarter of year 2022 compared to the previous year.

Table 28. Impact of I4.0 technologies on EEMs with the consideration of production resources and operational performances at Company B (textile and apparel manufacturer)

| I4.0 technologies | Cross Cutting Area | Energy Efficiency Measure | **Production Resources** | | | | | | | **Operational Performance** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Machine | Capital | Energy | Utilities and building | Human resources | Material and resources | Waste and emission | OEE | OLE | Operation Time | Throughput | Reliability | Productivity | Flexibility | Production speed | Operational cost |
| IoT | EM | Avoid rewinding motors more than twice | M / H | | M / N.O. | | | | | +/++ | | | | +/++ | | +/ × | | |
| | CA | Usage of compressor air filter | M / H | | | | | M / H | | +/++ | | | | +/ × | - / × | | | +/++ |
| | W | Usage of flow control valves to optimize water use | | | | | | M / H | | | | | | +/ × | | | | +/++ |
| AI | EM | Avoid rewinding motors more than twice | M / H | | M / H | | | | | +/ +++ | | | | +/ +++ | | +/ +++ | | |
| | CA | Usage of compressor air filter | M / H | | | | | M / H | | +/++ | | | | +/ +++ | - / ± | | | +/++ |
| | W | Usage of flow control valves to optimize water use | | | | | | M / H | M / H | | | | | +/++ | | | | +/ +++ |

Table 29. Impact of I4.0 technologies on EEMs with the consideration of production resources and operational performances at Company C (food processing company)

| I4.0 technologies | Cross Cutting Area | Energy Efficiency Measure | **Production Resources** | | | | | | | **Operational Performance** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Machine | Capital | Energy | Utilities and building | Human resources | Material and resources | Waste and emission | OEE | OLE | Operation Time | Throughput | Reliability | Productivity | Flexibility | Production speed | Operational cost |
| IoT | EM | Utilize energy efficient belts | M / H | | M / H | | | | | +/ +++ | - / - | | | +/++ | | | +/++ | |
| | CA | Maintain minimum pressure level for compressed air | M / H | | M / H | | | M / H | M / H | +/++ | | | | +/ +++ | | | | +/++ |
| | HVAC | Cleaning and maintenance of refrigerant condensers and towers | M / H | | | M / H | M / H | | | +/++ | +/++ | | | | | | | |

Note: In the impact matrix, first part shows the impact of EEM without considering I4.0 technology, second part shows the impact of EEM with the integration of specific I4.0 technology;
(1) High (H); Medium (M); Low (L); Not-observed (N.O.).
(2) Strongly positive (+++); Positive (++); Mildly Positive (+); Negative (-); Mixed (±); Not observed (×)

### 5.6 Discussion

The academic contribution of this study is developed based on two distinctive features mainly. First, this study has represented a novel attempt to explicitly consider EEMs impact on production resources & operational performances. Second, the study highlights the contribution of specific I4.0 technologies to boost performance of EEM at industrial context. To comply both features, the present research has done it by developing a framework to assess EEMs of based on the implications of a wider variety of production resources and operational performance metrics, further integrating I4.0 technologies for specific EEMs. The application of the framework in selected EEMs and I4.0 technologies allowed several interesting insights compared to extant literature.

#### 5.6.1 Impact of EEMs on production resources and operational performances

It should be remarked that the EEM characteristics are theoretically independent from each other, even though they might appear alongside each other in a few cases [86]. An initial observation, by looking at the framework (Table 23), is that EEMs appear to be significantly impacting core technical processes. In fact, this findings signifies the relation between EEMs and production process in industrial organizations [264]. For what concerns the production process, the majority of EEMs are related to electrical motors and compressed air, subsequently also acknowledged by energy efficiency experts during the validation phase of this framework.

By analyzing the framework and corroborated by the empirical findings of our investigation, we can observe that EEMs have critical implications on production resources at several levels. However, the implications depend on type of EEMs as well as cross cutting technologies. For majority of the cases, the impacted production resources are *machine*, *energy*, *material & resources*, and *waste & emission*. For example, *usage of adjustable frequency drive* is generally implied for energy savings in the electrical motor system. However, this EEM intervenes with the other machine in the sphere of production unit and impacts significantly. Likewise, *maintain minimum pressure level in compressed air* is referred as EEM, however, this EEM interposes in the overall manufacturing system and impacts on *energy*, *material & resources*, and *waste & emission*. Again, while looking at *cleaning & maintenance of refrigerants condensers and towers* in HVAC, we may observe an impact on *utilities & buildings*, and *human resources*. It should be acknowledged that the implications are justified on the overall production system in the company, allowing competitive advantage rather than energy efficiency perspective only.

Whilst looking at operational performances, we have observed positive implications of EEMs concerning electrical motor system, particularly on OEE improvement. In fact, the adherence of energy efficiency with equipment effectiveness is acknowledged in academia and industry [314], [315], although inadequately discussed. It is crucial to examine the machine effectiveness given that these attributes can help industrial decision makers to monitor operational performance in the industrial system. As to some extent expected (although not clearly acknowledged by previous literature), EEMs adoption has a major impact towards OEE. In particular, EEMs have a positive impact towards machine availability, performance improvement, and quality enhancement. For instance, "*avoid rewinding motors more than twic*e" has improved the machine performance by increasing the availability. It has also improved the reliability of the operation system in Company B (textile & apparel manufacturer). In fact, Company A (electronic appliance manufacturer) and Company C (food processing company) also have acknowledged significant implications on reliability concerning EEMs. This appears reasonable, as the EEMs are inclusively related to machine performance (and beyond) [40]. For example, *usage of compressed air filter* in the system allows the removal of contaminants, further helping the production system to work as planned. Likewise, *usage of flow control valve* in water system helps to optimize the water consumption. Generally, these EEMs act as a part of ancillary process in the industries and do not offer immediate advantage. Being that said, these EEMs significantly improve the process reliability in the system. In fact, this was the case of Company B (textile & apparel manufacturer) when considering the *usage of compressed air filter* and *flow control valve* in water system.

Earlier studies [7], [8], [10] have argued about few of the productivity benefits due to EEMs in an industrial context. Likewise, productivity features linking with EEMs are also highlighted by Trianni et al. [86]. However, inconclusive evidences are presented, as there is very little scientific understanding on how EEMs are impacting the company's productivity, specifically resource utilization. Nevertheless, it should be stated that while firms adopt EEMs, resource utilization is often improved which eventually leads to waste minimization or $CO_2$ emissions reduction [7]. For example, Company A (electronic appliance manufacturing) implemented usage of closed cycle process in the water system. It has acknowledged positive implications in productivity by reusing the water that have allowed reduced demand of fresh water in the manufacturing plant.

*Operational cost* represents a crucial factor to adopt any technical measure within industrial organizations. Marchi et al. [374] suggested that financial investment to adopt EEMs can lower operational cost and improve the quality of production processes. On the other hand, Fettermann [375], Tortorella [288] have also argued that I4.0 reduces the operational cost in the industrial manufacturing process. What matters here is that both the I4.0 and EEMs have the potential to minimize the operational cost. In fact, by looking at the application of this study, it is observed that I4.0 technologies have improved the performance of EEMs, leading to significant benefits in terms of operational costs. For instance, the adoption of sensors and AI in the computer aided HVAC system have allowed better monitoring and controlling of the plants' indoor environment, further, ensuring proper utilization of resource, eventually leading to reduction in operational cost. Furthermore, the positive impact in labour effectiveness is also observed in all the participated industries.

It should be acknowledged that whilst EEMs are capable to bring a large set of benefits, sometimes their implementation may negatively affect some operational performances. However, most of previous literature has neglected the negative implications of EEMs, overlooking the actual context of EEM's implication. In this regard, this study has clearly pinpointed negative impacts related to labour effectiveness and production speed for selected EEMs. For example, investigated companies noted that whilst energy efficient belts may improve the OEE, they also require additional maintenance work due to the additional retrofitting. Similarly, usage of filter in CAS improves the OEE, however, negatively affect the compressed air flow in the system.

Our findings seem to empirically showcase what previous studies were limited to theoretically highlight. Duflou et al. [264] argued about improvements in manufacturing systems by integrating energy efficient technologies covering redesign and optimization techniques, however, neglecting the broader attributes of production performance. Katic and Trianni [41] discussed the impact of production resources concerning EEMs, nonetheless, the consideration of operational performance is overlooked. Similarly, Hasan et al. [281] argued about the implication of EMS on production resources and productivity attributes, although, holistic consideration of operational performances are lacking. More recently, Cagno et al. [280] highlighted the impacts of EEMs at production level, however, the authors overlooked the holistic consideration of operational performance, resulting in a lack of empirical evidence.

It should be acknowledged that whilst the quantification of NEBs can be challenging and difficult to generalize across different business contexts [69] and result too burdensome or inadequate for smaller investments, qualitative knowledge of their impacts can significantly enrich the decision-making process. In this study, the qualitative approach highlighting the implications of EEMs in the decision-making process can well support industry decision-makers beyond considerations over energy savings.

### 5.6.2 Role of I4.0 to support specific EEM's performance

This investigation allowed to empirically showcase how EEMs and I4.0 technologies are intertwined and share similar objective which is to enhance the productivity and sustainability of a company, although potentially presenting different trajectories [60]. As somehow expected, while applying the framework in the investigated industries we have observed a substantial impact of I4.0 technologies boosting not just energy efficiency, rather improved a broad set of operational performances. The synergic use and management of machine data and hardware allows to reap unexploited benefits [376]. In fact, performance improvement options are not explored for the electrical motors adequately due to inadequate consideration of energy data. Furthermore, benchmarking of the machine performance in the manufacturing unit becomes difficult without comprehensive analysis of energy data [291]. This represented a major novelty with previous literature that has not sufficiently highlighted the contribution of I4.0 technologies in supporting the so-called non-energy benefits stemming from the adoption of EEMs [7], [8].

In the manufacturing plants, the energy flows are often found very complex due to involvement of multiple variables (e.g. forecasting, allocation, scheduling) in systems and processes. The participating companies have acknowledged the challenges of managing energy flows. However, with the help of CPS and Artificial intelligence platform, Company A and Company B have acknowledged improved control over the energy flows by leveraging the machine learning algorithms in electrical motor system, HVAC, CAS, and water system.

Similarly, while applying the framework, particularly in the electrical motors system, the differences in performances of motors are well observed with the help of IoT, which represented a crucial barrier to the adoption of EEMs due to the uncertainty in the effective performance [22], [121]. By connecting motors and other machinery, IoT provided more visibility of real time data in production system. In fact, IoT allowed to optimize the electricity consumption in motors and improved the quality of services by applying predictive maintenance. To some extent, the study has empirically shown that the improvement of operational performance stemming from the adoption of EEMs could be significantly improved (and documented) thanks to the adoption of I4.0 technologies. Related to this, the preliminary results of this study show that by coupling I4.0 technologies with EEMs would ultimately improve awareness and decision-making in industry, leading to improvements in specific operational performance.

With regards to I4.0 technologies, it can transform the large amount of operational data into actionable intelligence in industrial plants [273]. In fact, the sampled companies have acknowledged better performance in their operational activities by leveraging on a data driven approach. However, it was observed that it could be occasionally challenging to identify which specific I4.0 technology is suitable for boosting energy efficiency, being dependent on the specific needs and objectives of each application. For instance, in terms of metering & monitoring of energy status, sensors resulted quite useful. In fact, sensors become a critical component when it comes to identify the hot spots of energy usage as well as energy losses. When considering electrical motors system, compressed air system, HVAC, and water sensors acted quite significantly in Company A (electronic appliance manufacturer). Sensors have allowed better monitoring of energy consumption as well machine's operational status. Similarly, when it comes to control & optimization of energy flows, AI seems to have more useful. However, the combination of sensors and AI provide the best solution for metering, monitoring, and controlling of energy flows. On the contrary, some technologies may not have a specific impact on EEMs, whilst affecting the overall production system. For example, IRs are used in assembly unit for material handling, inspection and packaging in Company A. By looking at the mapping matrix, we have not observed any impact of IR into EEMs. However, industry participant have appreciated the overall positive implications stemming from IR in the manufacturing plant.

Whilst looking at the selection of I4.0 technologies, industry participants have argued that digital technologies certainly have a significant role in improving EEMs performance, although depending on the maturity level of the company in implementing the technologies, as explicitly noted by one of the interviewees: "*The utilization of digital technologies can be beneficial, in particular to improve the performance, facilitating the better monitoring and management of energy. However, higher maturity level of energy management in the company can be beneficial to capture the broader implications of technologies*".

Industry participants have also acknowledged that I4.0 technologies have improved not only the energy efficiency but also the operational activities in the plants. Company A, B, and C have confirmed that the technologies have improved the industrial processes and product quality. In fact, the use of I4.0 technologies have transformed the company's core competencies, also enabling the agility and mass customization in manufacturing [315], [375]. Also, the adoption of I4.0 technologies has helped industries towards a circular economy approach, as other studies are starting to highlight [377], [378].

This study, albeit it represents an exploratory investigation and further research in this domain is needed, has empirically shown that I4.0 technologies have an effective potential in supporting the transition of manufacturing system towards a more efficient use of production resources. Indeed, the investigation has provided evidence of beneficial impacts going beyond energy efficiency, rather extending to other production resources such as, e.g., materials, labour, and equipment. To this extent, the present study represents an advancement to academic literature with respect to earlier studies trying to discuss the impact of EEMs towards other production resources [40].

### 5.7 Summary

An exploratory study highlighting the role of I4.0 in terms of EEMs with the impact of production resources and operational performances are presented in this chapter. To support the objective of the investigation, a novel framework has been developed and applied with respect to a subset of I4.0 technologies and EEMs. The framework is developed encompassing the characterization of EEMs by linking the implications on production resources and operational performance, further integrating I4.0 technologies in an industrial context.

For the exploratory investigation in manufacturing companies, EEMs from cross-cutting technologies and some I4.0 technologies such as Cyber Physical System, Artificial Intelligence (AI), Internet of Things (IoT), and industrial robots (IR) are selected. The study shows that the synergic use and management of machine data and hardware allows to reap unexploited benefits beyond energy efficiency, such as overall equipment effectiveness (OEE), labour effectiveness, reliability, reduced operational costs. The study also reveals the contribution of specific I4.0 technologies with respect to specific EEMs: whilst implementing AI is deemed important for boosting the benefits of programming HVAC and closed cycle process in water management (improving OEE, productivity and reducing operational costs), IoT seems to beneficially affect the adoption of motor systems by improving OEE and reliability.

# Chapter 6

……………………………………………………………………………………………………………

*This chapter begins with a synthesis of the outcome of the thesis, followed by future research directions.*

## 6. Conclusion

This thesis summarizes several intertwined issues in industrial energy management. The thesis is started with the review of existing energy management models followed by the investigation of energy management practices, drivers & barriers to EE, barriers to ESCOs. In the later phase, a novel characterization based framework is developed encompassing EMS, production resources, & productivity further highlighting the implications of EMS on production resources and productivity features. The last phase of the thesis is focused at exploring the role Industry 4.0 technologies in the adoption of EEMs with impact on production resources and operational performances.

A comprehensive review of research on industrial energy management models are presented in Chapter 2 synthesizing frameworks to offer necessary benchmarks for industrial experts. However, several complex research gaps were identified, including the lack of consideration for energy management services in relation to production resources, the effect of EEMs on operational performance in an industrial context, and the integration of EE features offered by I4.0. An integrated approach is necessary to understand operational activities within industrial organizations and achieve better sustainability metrics.

In Chapter 3, a comprehensive investigation was performed to explore energy management and its practices, together with barriers and drivers to energy efficiency as well as barriers to ESCOs, in the context of energy intensive industries in a developing Asian economy. The results of investigation could provide significant insights into the energy management domain also for energy policy-makers. As major remark, the empirical findings show that the concept of energy management and energy efficiency is relatively new in the investigated industries, with lack of awareness and information systems deemed as quite critical for companies. This is particularly critical, as awareness on the importance of energy management and energy efficiency constitute a steppingstone for any further improvement project. In addition, it is observed that absence of energy manager or limited authority of energy manager has impact on barriers to energy efficiency. Nonetheless, the significance of energy monitoring has been pointed out, which is essential for increased knowledge and decision making.

Furthermore, the investigated sample revealed an above-average potential of energy efficiency: this important result call for a greater effort by research, policy-making and industry to boost industrial energy efficiency within developing economies, where too little (e.g. small educational projects, financial loans) has been made so far. Nonetheless, industries are still lagging behind in the implementation of energy efficiency solutions and energy management practices. Interestingly, the study has pointed out that in the investigated context, companies may be challenged, beyond the well-known technical and economic barriers, also by organizational ones. Further, thanks to a preliminary correlation analysis, several potential correlations are pointed out among barriers and drivers that could give policy-makers valuable insights on the major obstacles and leverages to promote industrial energy management and energy efficiency. The preliminary results seem to suggest that further policy-making efforts should be placed to better integrate energy management into industries' organizational structures.

In this theses, Chapter 4 presents a framework that characterizes industrial EMSs and their impact on production resources and productivity features, which is a novel approach as prior studies have not examined EMSs in such detail. The framework includes a comprehensive set of EMSs with a defined set of attributes that allow for the consideration of different perspectives, enabling industrial organizations to identify significant factors impacting their production resources and operational performance. This is accomplished by explicitly taking into consideration the characteristics of energy management services based on 25 attributes belonging to four categories i. e., implementation, impacted area, impact on production resources and productivity. In addition, the study shed further light on the practical implementation of energy management activities by also placing focus on the link between the implications of their adoption on production resources and the subsequent impact on industrial operations.

In a general sense, the output of the developed framework is more inclusive than existing EM schemes or a mere appraisal of the maturity level, given the meticulous assessment of the EMSs involved in the decision-making process. By considering the framework, industrial organizations have the ability to highlight any significant factors impacting their operational performance, paving the way towards a detailed strategy for EM. It is for this reason that a comprehensive set of EMSs are developed with a defined set of attributes. Such an approach thus allows for the consideration of several important viewpoints to assess EMS adoption, specifically the capabilities and organizational perspectives, and suggest specific actions for each EMS. The developed framework also signifies the relevant concerns in EM supply chains within the industrial decision making and policy making process.

Chapter 5 investigates the contribution of I4.0 technologies in the adoption of EEMs with impact on production resources and operational performances. For industrial decision-makers, this poses an important consideration since it illustrates the correlation between production resources and operational effectiveness. Particularly, the characterization of the operational performance attributes enables a holistic view of EEMs, leading to a more precise approach for selecting the appropriate EEMs to be applied. To support the objective of the investigation, a novel framework has been developed and applied with respect to a subset of I4.0 technologies and EEMs. By applying the framework, industrial companies can pinpoint the critical issues affecting their operational performance as well as further improvement with the help of I4.0 technologies, with particular emphasis on the adoption of EEMs, thus improving the decision-making process over their adoption.

The framework for exploratory investigation in manufacturing companies involves selecting multiple EEMs covering electrical motor system, CAS, HVAC, water system and using a sub-set of I4.0 technologies including CPS, AI, IoT, and IR. As major remark, the empirical findings show that the synergic use and management of machine data and hardware allows to reap unexploited benefits beyond energy efficiency, such as overall equipment effectiveness (OEE), labour effectiveness, reliability, reduced operational costs. The study also reveals the contribution of specific I4.0 technologies with respect to specific EEMs: whilst implementing AI is deemed important for boosting the benefits of programming HVAC and closed cycle process in water management (improving OEE, productivity and reducing operational costs), IoT seems to beneficially affect the adoption of motor systems by improving OEE and reliability

In summary, the findings of this thesis reveals several intertwined issues within the realm of energy management and I4.0. Primarily, the thesis sought to address the existing gaps in understanding energy management practices, barriers, and drivers to energy efficiency, and barriers to ESCOs in industrial contexts. By delving into these crucial aspects, the aim is to unveil critical insights that could pave the way for optimized energy management strategies. Secondly, the thesis introduces an innovative framework that encompasses EMS, production resources, and productivity features. This framework facilitates a broader perspective on the significance of EMS, extending its influence on areas beyond energy savings. Lastly, the thesis concludes by developing a framework that aims to showcase the role of I4.0 in augmenting the performance of EEMs, taking into account the impact of production resources and operational performance at shop floor level. Despite the specific application, the framework stands out due to its distinctive capability to assess the impact of specific I4.0 technologies on EEMs at an operational level. This unique feature is of particular significance to industrial decision-makers who seek to identify the potential benefits and challenges associated with adopting these technologies in their operations. Through the utilization of this framework, decision-makers can make well-informed choices regarding which I4.0 technologies to invest in and how to optimize their implementation to achieve the greatest impact on EEM.

## Limitation & future work

It is worth remarking few main limitations that offer opportunities for future research of this thesis. ***Firstly***, while investigating the energy management practices at industries, we could not perform intensive statistical tests due to a lesser number of data. Besides, a comparison across a number of companies with different contextual factors (e.g. firm size, energy intensity type) have not investigated with respect to specific EEMs, for which slight differences may be expected. Moreover, the current investigation delves into energy-intensive industries without specifying a particular industry type. However, in future research endeavours, a directed approach could be adopted by selecting specific sectors (e.g. steel, cement, textile). This strategic shift towards examining particular sectors allows for a more thorough understanding because the nature of energy consumption varies significantly based on the industry. Additionally, the research will extend its focus to Small and Medium-sized Enterprises (SMEs). Recognising that the nature of energy consumption in SMEs differs from that of large energy-intensive industries, this inclusion ensures a more comprehensive exploration of the diverse energy consumption patterns across different industrial scales. Furthermore, it is imperative to acknowledge that the barriers and drivers to energy efficiency exhibit variations from country to country. To date, there is a lack of studies that comprehensively highlight the diverse barriers and drivers influencing energy efficiency across different countries. Addressing this gap in research will contribute significantly to understanding the contextual nuances that shape energy management practices on a global scale.

***Secondly***, in developing the framework encompassing EMS, the quantitative metrics featuring production resources and productivity attributes are not considered. Therefore, forthcoming research should integrate a more comprehensive consideration of production resources. Specifically, an in-depth examination of "capital" or financial resources is imperative. For instance, in analysing the impact of an EMS, a thorough investigation of their influence on “capital” or financial resources should be integrated by expanding the scope of cost-benefit analysis over EMS adoption to further assess their profitability within the industrial sector. Furthermore, with regard to material and resources, a deeper look into the impact of EMS is required incorporating specific metrics related to material consumption, waste generation, and overall resource efficiency. Besides, there is a need to encompass a broader spectrum of operational features. For instance, specific metrics could include availability of machine, labour, resource management and utilization, and energy consumption per unit of output. Integrating such operational considerations into the analysis will provide a more nuanced understanding of the impact of EMS adoption on overall production resources within industrial settings.

***Thirdly***, whilst investigating the role of I4.0 with respect to EEMS, the thesis has focused to a specific set of I4.0 technologies and EEMs, thus not encompassing in the analysis all I4.0 technologies. Although it may be not practical to include every possible technology in the empirical analysis, the theoretical framework developed to support the empirical investigation has been designed to be flexible enough to accommodate any I4.0 technology, without being dependent on its specific features. Besides, the application has been limited to a set of EEMs, and there is no quantification of the impact assessment. Indeed, future studies should on the one hand expand the investigated sample to achieve statistical significance over the effective contribution of specific I4.0 technologies in boosting specific EEMs performance. On the other hand, research should explore quantitative metrics to detail the impact of I4.0 technologies and EEMs on operations performance. This entails moving beyond qualitative assessments and embracing a more rigorous approach that involves numerical and measurable indicators. For instance, the examination of metrics related to production cycle times, energy consumption, and resource utilization can offer valuable insights into the quantitative impact on overall operations performance. However, even the qualitative findings discussed in this study represent a major step to support industry in the decision-making process of adopting specific I4.0 technologies and EEMs. Hence, future research should expand towards encompassing a wider range of I4.0 and cross-cutting technologies, to further examine the role of I4.0 to support a more widespread adoption of energy efficiency measures. In fact, it would be really interesting to observe the diverse array of technologies within the I4.0 framework, ranging from IoT devices and AI to advanced sensors and blockchain and how the technologies can best support the performance of EEMs with the impact of operational performances. This holistic exploration will not only shed light on the technological nuances but also pave the way for informed strategies that can propel a sustainable and efficient industrial landscape integrating EEMs, I4.0, and operational performances.

## References


[1] "International Energy Outlook 2019 with projections to 2050," Washington, DC, USA, 2019. [Online]. Available: http://choicereviews.org/review/10.5860/CHOICE.44-3624.

[2] International Energy Agency, "World Energy Outlook 2022," Paris, 2022. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2022.

[3] "Energy efficiency," 2022. https://www.iea.org/topics/energy-efficiency (accessed Feb. 20, 2022).

[4] "Net zero by 2050 hinges on a global push to increase energy efficiency – Analysis - IEA." https://www.iea.org/articles/net-zero-by-2050-hinges-on-a-global-push-to-increase-energy-efficiency (accessed Feb. 20, 2022).

[5] "Energy Efficiency 2021 – Analysis - IEA," 2021. https://www.iea.org/reports/energy-efficiency-2021 (accessed May 10, 2022).

[6] "Productivity – Multiple Benefits of Energy Efficiency – Analysis - IEA." https://www.iea.org/reports/multiple-benefits-of-energy-efficiency/productivity (accessed Jun. 26, 2023).

[7] E. Worrell, J. A. Laitner, M. Ruth, and H. Finman, "Productivity benefits of industrial energy efficiency measures," *Energy*, vol. 28, no. 11, pp. 1081–1098, Sep. 2003, doi: 10.1016/S0360-5442(03)00091-4.

[8] H. Finman and J. A. Laitner, "Industry, energy efficiency and productivity improvements," in *Proceedings ACEEE Summer Study on Energy Efficiency in Industry*, 2001, vol. 1, pp. 561–570, [Online]. Available: https://www.aceee.org/files/proceedings/2001/data/index.htm.

[9] L. A. Skumatz and C. A. Dickerson, "Extra ! Extra ! Non-Energy Benefits Swamp Load Impacts For PG&E Program !," in *Proceedings of the 1998 ACEEE summer study, Panel 8.*, 1998, pp. 301–312, [Online]. Available: https://www.aceee.org/files/proceedings/1998/data/index.htm.

[10] T. Nehler and J. Rasmussen, "How do firms consider non-energy benefits? Empirical findings on energy-efficiency investments in Swedish industry," *J. Clean. Prod.*, vol. 113, pp. 472–482, Feb. 2016, doi: 10.1016/j.jclepro.2015.11.070.

[11] "Capturing the Multiple Benefits of Energy Efficiency," 2014. doi: 10.1787/9789264220720-en.

[12] "Energy Efficiency 2019 – Analysis - IEA," 2019. https://www.iea.org/reports/energy-efficiency-2019#key-findings (accessed Jan. 11, 2021).

[13] A. B. Jaffe and R. N. Stavins, "The energy-efficiency gap What does it mean?," *Energy Policy*, vol. 22, no. 10, pp. 804–810, Oct. 1994, doi: 10.1016/0301-4215(94)90138-4.

[14] M. T. Johansson, "Improved energy efficiency within the Swedish steel industry—the importance of energy management and networking," *Energy Effic.*, vol. 8, no. 4, pp. 713–744, Jul. 2015, doi: 10.1007/s12053-014-9317-z.

[15] S. Backlund, P. Thollander, J. Palm, and M. Ottosson, "Extending the energy efficiency gap," *Energy Policy*, vol. 51, pp. 392–396, Dec. 2012, doi: 10.1016/j.enpol.2012.08.042.

[16] S. S. Steve Sorrell, Eoin O'Malley, Joachim Schleich, *The Economics of Energy Effieincy: Barriers to Cost-Effective Investment*. Edward Elgar Publishing, 2004.

[17] E. Cagno, E. Worrell, A. Trianni, and G. Pugliese, "A novel approach for barriers to industrial energy efficiency," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 290–308, Mar. 2013, doi: 10.1016/j.rser.2012.11.007.

[18] J. C. Brunke, M. Johansson, and P. Thollander, "Empirical investigation of barriers and drivers to the adoption of energy conservation measures, energy management practices and energy services in the Swedish iron and steel industry," *J. Clean. Prod.*, vol. 84, no. 1, pp. 509–525, Dec. 2014, doi: 10.1016/j.jclepro.2014.04.078.

[19] A. S. M. M. Hasan *et al.*, "Drivers and Barriers to Industrial Energy Efficiency in Textile Industries of Bangladesh," *Energies*, vol. 12, no. 9, p. 1775, May 2019, doi: 10.3390/en12091775.

[20] A. Soepardi and P. Thollander, "Analysis of Relationships among Organizational Barriers to Energy Efficiency Improvement: A Case Study in Indonesia's Steel Industry," *Sustainability*, vol. 10, no. 1, p. 216, Jan. 2018, doi: 10.3390/su10010216.

[21] A. Trianni, E. Cagno, P. Thollander, and S. Backlund, "Barriers to industrial energy efficiency in foundries: A European comparison," *J. Clean. Prod.*, vol. 40, pp. 161–176, Feb. 2013, doi: 10.1016/j.jclepro.2012.08.040.

[22] A. Trianni, E. Cagno, and S. Farné, "Barriers, drivers and decision-making process for industrial energy efficiency: A broad study among manufacturing small and medium-sized enterprises," *Appl. Energy*, vol. 162, pp. 1537–1551, Jan. 2016, doi: 10.1016/j.apenergy.2015.02.078.

[23] E. Cagno, A. Trianni, G. Spallina, and F. Marchesani, "Erratum to: Drivers for energy efficiency and their effect on barriers: empirical evidence from Italian manufacturing enterprises," *Energy Effic.*, vol. 10, no. 4, pp. 871–871, Aug. 2017, doi: 10.1007/s12053-016-9498-8.

[24] A. Trianni, E. Cagno, F. Marchesani, and G. Spallina, "Classification of drivers for industrial energy efficiency and their effect on the barriers affecting the investment decision-making process," *Energy Effic.*, vol. 10, no. 1, pp. 199–215, Feb. 2017, doi: 10.1007/s12053-016-9455-6.

[25] R. W. Apeaning and P. Thollander, "Barriers to and driving forces for industrial energy efficiency improvements in African industries – a case study of Ghana's largest industrial area," *J. Clean. Prod.*, vol. 53, pp. 204–213, Aug. 2013, doi: 10.1016/j.jclepro.2013.04.003.

[26] A. Trianni, E. Cagno, M. Bertolotti, P. Thollander, and E. Andersson, "Energy management: A practice-based assessment model," *Appl. Energy*, vol. 235, pp. 1614–1636, Feb. 2019, doi: 10.1016/j.apenergy.2018.11.032.

[27] A. S. M. M. Hasan, M. T. Hoq, and P. Thollander, "Energy management practices in

Bangladesh's iron and steel industries," *Energy Strateg. Rev.*, vol. 22, pp. 230–236, Nov. 2018, doi: 10.1016/j.esr.2018.09.002.

[28] P. Thollander and M. Ottosson, "Energy management practices in Swedish energy-intensive industries," *J. Clean. Prod.*, vol. 18, no. 12, pp. 1125–1133, Aug. 2010, doi: 10.1016/j.jclepro.2010.04.011.

[29] A. S. M. M. Hasan, R. Hossain, R. A. Tuhin, T. H. Sakib, and P. Thollander, "Empirical Investigation of Barriers and Driving Forces for Efficient Energy Management Practices in Non-Energy-Intensive Manufacturing Industries of Bangladesh," *Sustainability*, vol. 11, no. 9, p. 2671, May 2019, doi: 10.3390/su11092671.

[30] A. Sa, S. Paramonova, P. Thollander, and E. Cagno, "Classification of Industrial Energy Management Practices: A Case Study of a Swedish Foundry," *Energy Procedia*, vol. 75, pp. 2581–2588, Aug. 2015, doi: 10.1016/j.egypro.2015.07.311.

[31] S. Backlund; P. Thollander, "The energy-service gap. What does it mean?," in *ECEEE 2011 Summer Study*, 2011, pp. 649–656, Accessed: Apr. 15, 2020. [Online]. Available: https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2011/3-energy-use-in-industry-the-road-from-policy-to-action/the-energy-service-gap-what-does-it-mean/.

[32] N. Good, E. A. Martínez Ceseña, L. Zhang, and P. Mancarella, "Techno-economic and business case assessment of low carbon technologies in distributed multi-energy systems," *Appl. Energy*, vol. 167, pp. 158–172, Apr. 2016, doi: 10.1016/j.apenergy.2015.09.089.

[33] A. S. M. Monjurul Hasan, A. Trianni, N. Shukla, and M. Katic, "A novel characterization based framework to incorporate industrial energy management services," *Appl. Energy*, vol. 313, p. 118891, May 2022, doi: 10.1016/J.APENERGY.2022.118891.

[34] L. Zhou, J. Li, F. Li, Q. Meng, J. Li, and X. Xu, "Energy consumption model and energy efficiency of machine tools: A comprehensive literature review," *Journal of Cleaner Production*. 2016, doi: 10.1016/j.jclepro.2015.05.093.

[35] M. M. Akan, A. S. Fung, and R. Kumar, "Process energy analysis and saving opportunities in small and medium size enterprises for cleaner industrial production," *J. Clean. Prod.*, 2019, doi: 10.1016/j.jclepro.2019.06.046.

[36] A. S. M. M. Hasan and A. Trianni, "A Review of Energy Management Assessment Models for Industrial Energy Efficiency," *Energies*, vol. 13, no. 21, p. 5713, Nov. 2020, doi: 10.3390/en13215713.

[37] K. Bunse, M. Vodicka, P. Schönsleben, M. Brülhart, and F. O. Ernst, "Integrating energy efficiency performance in production management - Gap analysis between industrial needs and scientific literature," *J. Clean. Prod.*, vol. 19, no. 6–7, pp. 667–679, Apr. 2011, doi: 10.1016/j.jclepro.2010.11.011.

[38] V. Thakur and S. K. Mangla, "Change management for sustainability: Evaluating the role of

human, operational and technological factors in leading Indian firms in home appliances sector," *J. Clean. Prod.*, vol. 213, pp. 847–862, Mar. 2019, doi: 10.1016/J.JCLEPRO.2018.12.201.

[39] R. Siegel, J. Antony, J. A. Garza-Reyes, A. Cherrafi, and B. Lameijer, "Integrated green lean approach and sustainability for SMEs: From literature review to a conceptual framework," *Journal of Cleaner Production*. 2019, doi: 10.1016/j.jclepro.2019.118205.

[40] A. Trianni, E. Cagno, J. Dolšak, and N. Hrovatin, "Implementing energy efficiency measures: do other production resources matter? A broad study in Slovenian manufacturing small and medium-sized enterprises," *J. Clean. Prod.*, vol. 287, p. 125044, Mar. 2021, doi: 10.1016/j.jclepro.2020.125044.

[41] M. Katic and A. Trianni, "Energy efficiency measures and production resources: Towards an integrative classification framework for decision makers," in *IEEE International Conference on Industrial Engineering and Engineering Management*, 2020, vol. 2020-Decem, pp. 225–229, doi: 10.1109/IEEM45057.2020.9309836.

[42] R. Kannan and W. Boie, "Energy management practices in SME - Case study of a bakery in Germany," *Energy Convers. Manag.*, vol. 44, no. 6, pp. 945–959, Apr. 2003, doi: 10.1016/S0196-8904(02)00079-1.

[43] M. Schulze, H. Nehler, M. Ottosson, and P. Thollander, "Energy management in industry – a systematic review of previous findings and an integrative conceptual framework," *J. Clean. Prod.*, vol. 112, pp. 3692–3708, Jan. 2016, doi: 10.1016/j.jclepro.2015.06.060.

[44] A. G. Frank, L. S. Dalenogare, and N. F. Ayala, "Industry 4.0 technologies: Implementation patterns in manufacturing companies," *Int. J. Prod. Econ.*, vol. 210, pp. 15–26, Apr. 2019, doi: 10.1016/j.ijpe.2019.01.004.

[45] N. Mohamed, J. Al-Jaroodi, and S. Lazarova-Molnar, "Leveraging the Capabilities of Industry 4.0 for Improving Energy Efficiency in Smart Factories," *IEEE Access*, vol. 7, pp. 18008–18020, 2019, doi: 10.1109/ACCESS.2019.2897045.

[46] F. S. Tesch da Silva, C. A. da Costa, C. D. Paredes Crovato, and R. da Rosa Righi, "Looking at energy through the lens of Industry 4.0: A systematic literature review of concerns and challenges," *Comput. Ind. Eng.*, vol. 143, p. 106426, May 2020, doi: 10.1016/j.cie.2020.106426.

[47] M. Ghobakhloo and M. Fathi, "Industry 4.0 and opportunities for energy sustainability," *J. Clean. Prod.*, 2021, doi: 10.1016/j.jclepro.2021.126427.

[48] L. Bukata, P. Šůcha, and Z. Hanzálek, "Optimizing energy consumption of robotic cells by a Branch & Bound algorithm," *Comput. Oper. Res.*, vol. 102, pp. 52–66, Feb. 2019, doi: 10.1016/j.cor.2018.09.012.

[49] S. Wan, Y. Zhao, T. Wang, Z. Gu, Q. H. Abbasi, and K. K. R. Choo, "Multi-dimensional data indexing and range query processing via Voronoi diagram for internet of things," *Futur. Gener. Comput. Syst.*, vol. 91, pp. 382–391, Feb. 2019, doi: 10.1016/j.future.2018.08.007.

[50] Y. Duan, Y. Luo, W. Li, P. Pace, G. Aloi, and G. Fortino, "A collaborative task-oriented

scheduling driven routing approach for industrial IoT based on mobile devices," *Ad Hoc Networks*, vol. 81, pp. 86–99, Dec. 2018, doi: 10.1016/j.adhoc.2018.07.022.

[51] K. Bruton, B. P. Walsh, D. Ó. Cusack, P. O'Donovan, and D. T. J. O'Sullivan, "Enabling Effective Operational Decision Making on a Combined Heat and Power System Using the 5C Architecture," in *Procedia CIRP*, Jan. 2016, vol. 55, pp. 296–301, doi: 10.1016/j.procir.2016.08.036.

[52] L. Valerio, M. Conti, and A. Passarella, "Energy efficient distributed analytics at the edge of the network for IoT environments," *Pervasive Mob. Comput.*, vol. 51, pp. 27–42, Dec. 2018, doi: 10.1016/j.pmcj.2018.09.004.

[53] E. Baccarelli, P. G. V. Naranjo, M. Scarpiniti, M. Shojafar, and J. H. Abawajy, "Fog of Everything: Energy-Efficient Networked Computing Architectures, Research Challenges, and a Case Study," *IEEE Access*, vol. 5, pp. 9882–9910, 2017, doi: 10.1109/ACCESS.2017.2702013.

[54] M. Faheem and V. C. Gungor, "Energy efficient and QoS-aware routing protocol for wireless sensor network-based smart grid applications in the context of industry 4.0," *Appl. Soft Comput. J.*, vol. 68, pp. 910–922, Jul. 2018, doi: 10.1016/j.asoc.2017.07.045.

[55] S. Montero, J. Gozalvez, and M. Sepulcre, "Neighbor discovery for industrial wireless sensor networks with mobile nodes," *Comput. Commun.*, vol. 111, pp. 41–55, Oct. 2017, doi: 10.1016/j.comcom.2017.07.004.

[56] S. Bag, G. Yadav, P. Dhamija, and K. K. Kataria, "Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: An empirical study," *J. Clean. Prod.*, vol. 281, p. 125233, Jan. 2021, doi: 10.1016/J.JCLEPRO.2020.125233.

[57] C. Bai, G. Orzes, and J. Sarkis, "Exploring the impact of Industry 4.0 technologies on social sustainability through a circular economy approach," *Ind. Mark. Manag.*, vol. 101, pp. 176–190, Feb. 2022, doi: 10.1016/j.indmarman.2021.12.004.

[58] J. Oláh, N. Aburumman, J. Popp, M. A. Khan, H. Haddad, and N. Kitukutha, "Impact of Industry 4.0 on Environmental Sustainability," *Sustainability*, vol. 12, no. 11, p. 4674, 2020, doi: 10.3390/su12114674.

[59] M. Calış Duman and B. Akdemir, "A study to determine the effects of industry 4.0 technology components on organizational performance," *Technol. Forecast. Soc. Change*, vol. 167, p. 120615, Jun. 2021, doi: 10.1016/J.TECHFORE.2021.120615.

[60] F. Shrouf and G. Miragliotta, "Energy management based on Internet of Things: Practices and framework for adoption in production management," *J. Clean. Prod.*, vol. 100, pp. 235–246, Aug. 2015, doi: 10.1016/j.jclepro.2015.03.055.

[61] F. Shrouf, B. Gong, and J. Ordieres-Meré, "Multi-level awareness of energy used in production processes," *J. Clean. Prod.*, vol. 142, pp. 2570–2585, Jan. 2017, doi: 10.1016/j.jclepro.2016.11.019.

[62] S. Wang, J. Wan, D. Zhang, D. Li, and C. Zhang, "Towards smart factory for industry 4.0: A

self-organized multi-agent system with big data based feedback and coordination," *Comput. Networks*, vol. 101, pp. 158–168, Jun. 2016, doi: 10.1016/j.comnet.2015.12.017.

[63] T. Javied, T. Rackow, and J. Franke, "Implementing Energy Management System to Increase Energy Efficiency in Manufacturing Companies," *Procedia CIRP*, vol. 26, no. January, pp. 156–161, 2015, doi: 10.1016/j.procir.2014.07.057.

[64] W. K. BL Capehart, WC Turner, *Guide to Energy Management*, Fifth Edit. The Fairmont Press, 2006.

[65] P. W. O'Callaghan and S. D. Probert, "Energy management," *Appl. Energy*, vol. 3, no. 2, pp. 127–138, Apr. 1977, doi: 10.1016/0306-2619(77)90024-1.

[66] S. A. Ates and N. M. Durakbasa, "Evaluation of corporate energy management practices of energy intensive industries in Turkey," *Energy*, vol. 45, no. 1, pp. 81–91, Sep. 2012, doi: 10.1016/j.energy.2012.03.032.

[67] E. A. Abdelaziz, R. Saidur, and S. Mekhilef, "A review on energy saving strategies in industrial sector," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1. Pergamon, pp. 150–168, Jan. 01, 2011, doi: 10.1016/j.rser.2010.09.003.

[68] L. B. Christoffersen, A. Larsen, and M. Togeby, "Empirical analysis of energy management in Danish industry," *J. Clean. Prod.*, vol. 14, no. 5, pp. 516–526, Jan. 2006, doi: 10.1016/j.jclepro.2005.03.017.

[69] J. Rasmussen, "The additional benefits of energy efficiency investments—a systematic literature review and a framework for categorisation," *Energy Effic.*, vol. 10, no. 6, pp. 1401–1418, 2017, doi: 10.1007/s12053-017-9528-1.

[70] A. Mckane, R. Williams, and W. Perry, "Setting the Standard for Industrial Energy Efficiency Permalink," Jun. 2008, Accessed: Apr. 20, 2020. [Online]. Available: http://www.eere.energy.gov/industry/energy_systems/analysis.html.

[71] "ISO 50001:2018(en), Energy management systems — Requirements with guidance for use." https://www.iso.org/obp/ui/#iso:std:iso:50001:ed-2:v1:en (accessed Oct. 18, 2020).

[72] V. Introna, V. Cesarotti, M. Benedetti, S. Biagiotti, and R. Rotunno, "Energy Management Maturity Model: an organizational tool to foster the continuous reduction of energy consumption in companies," *J. Clean. Prod.*, vol. 83, pp. 108–117, Nov. 2014, doi: 10.1016/j.jclepro.2014.07.001.

[73] A. Sa, P. Thollander, and E. Cagno, "Assessing the driving factors for energy management program adoption," *Renewable and Sustainable Energy Reviews*, vol. 74. Elsevier Ltd, pp. 538–547, Jul. 01, 2017, doi: 10.1016/j.rser.2017.02.061.

[74] C. V. Weber, B. Curtis, and M. B. Chrissis, "Capability Maturity Model, Version 1.1," *IEEE Softw.*, vol. 10, no. 4, pp. 18–27, 1993, doi: 10.1109/52.219617.

[75] J. Becker, R. Knackstedt, and J. Pöppelbuß, "Developing Maturity Models for IT Management," *Bus. Inf. Syst. Eng.*, vol. 1, no. 3, pp. 213–222, Jun. 2009, doi: 10.1007/s12599-009-0044-5.

[76] J. E. Scott, “Mobility, business process management, software sourcing, and maturity model trends: Propositions for the IS organization of the future,” *Inf. Syst. Manag.*, vol. 24, no. 2, pp. 139–145, Jan. 2007, doi: 10.1080/10580530701221031.

[77] G. Lahrmann, F. Marx, T. Mettler, R. Winter, and F. Wortmann, *Inductive design of maturity models: Applying the Rasch algorithm for design science research*, vol. 6629 LNCS. Springer, Berlin, Heidelberg, 2011.

[78] CMMI Product Team, “CMMI for Development, Version 1.3,” Software Engineering Institute, Carnegie Mellon University, 2010. doi: CMU/SEI-2010-TR-033 ESC-TR-2010-033.

[79] D. Proença and J. Borbinha, “Maturity Models for Information Systems - A State of the Art,” in *Procedia Computer Science*, Jan. 2016, vol. 100, pp. 1042–1049, doi: 10.1016/j.procs.2016.09.279.

[80] B. Jovanović and J. Filipović, “ISO 50001 standard-based energy management maturity model – proposal and validation in industry,” *J. Clean. Prod.*, vol. 112, pp. 2744–2755, Jan. 2016, doi: 10.1016/j.jclepro.2015.10.023.

[81] E. W. T. Ngai, D. C. K. Chau, J. K. L. Poon, and C. K. M. To, “Energy and utility management maturity model for sustainable manufacturing process,” *Int. J. Prod. Econ.*, vol. 146, no. 2, pp. 453–464, Dec. 2013, doi: 10.1016/j.ijpe.2012.12.018.

[82] D. Gordić, M. Babić, N. Jovičić, V. Šušteršič, D. Končalović, and D. Jelić, “Development of energy management system - Case study of Serbian car manufacturer,” *Energy Convers. Manag.*, vol. 51, no. 12, pp. 2783–2790, Dec. 2010, doi: 10.1016/j.enconman.2010.06.014.

[83] “Energy management- A comprehensive guide to controlling energy use.” Carbon Trust, London, United Kingdom, p. 53, 2011.

[84] “ENERGY STAR Guidelines for Energy Management | | ENERGY STAR,” 2012. Accessed: Apr. 12, 2020. [Online]. Available: https://www.energystar.gov/buildings/tools-and-resources/energy-star-guidelines-energy-management.

[85] T. Fleiter, S. Hirzel, and E. Worrell, “The characteristics of energy-efficiency measures - a neglected dimension,” *Energy Policy*, vol. 51, pp. 502–513, Dec. 2012, doi: 10.1016/j.enpol.2012.08.054.

[86] A. Trianni, E. Cagno, and A. De Donatis, “A framework to characterize energy efficiency measures,” *Appl. Energy*, vol. 118, pp. 207–220, Apr. 2014, doi: 10.1016/j.apenergy.2013.12.042.

[87] Robert Bruce Lung; Aimee McKane; Robert Leach; Donald Marsh, “Ancillary Savings and Production Benefits in the Evaluation of Industrial Energy Efficiency Measures,” *Proceedings ACEEE Summer Studies on Energy Efficiency in Industry*. Berkeley, CA, US., pp. 103–114, 2005, Accessed: Apr. 29, 2020. [Online]. Available: https://www.eceee.org/library/conference_proceedings/ACEEE_industry/2005/Panel_6/p6_10/ .

[88] S. Sorrell, “The economics of energy service contracts,” *Energy Policy*, vol. 35, no. 1, pp. 507–521, Jan. 2007, doi: 10.1016/j.enpol.2005.12.009.

[89] M. Benedetti, V. Cesarotti, M. Holgado, V. Introna, and M. Macchi, “A proposal for energy services’ classification including a product service systems perspective,” in *Procedia CIRP*, Jan. 2015, vol. 30, pp. 251–256, doi: 10.1016/j.procir.2015.02.121.

[90] P. Antunes, P. Carreira, and M. Mira da Silva, “Towards an energy management maturity model,” *Energy Policy*, vol. 73, pp. 803–814, Oct. 2014, doi: 10.1016/j.enpol.2014.06.011.

[91] O. J, “Energy Management Maturity Model (EM3),” 2012.

[92] N. Finnerty, R. Sterling, D. Coakley, and M. M. Keane, “An energy management maturity model for multi-site industrial organisations with a global presence,” *J. Clean. Prod.*, vol. 167, pp. 1232–1250, Nov. 2017, doi: 10.1016/j.jclepro.2017.07.192.

[93] A. Prashar, “Energy efficiency maturity (EEM) assessment framework for energy-intensive SMEs: Proposal and evaluation,” *J. Clean. Prod.*, vol. 166, pp. 1187–1201, Nov. 2017, doi: 10.1016/j.jclepro.2017.08.116.

[94] C. J. Ashford, “Energy Efficiency: A Managed Resource,” *Facilities*, vol. 11, no. 4, pp. 24–27, Jan. 1993, doi: 10.1108/EUM0000000002237.

[95] “ISO 50001:2011(en), Energy management systems — Requirements with guidance for use.” https://www.iso.org/obp/ui/#iso:std:iso:50001:ed-1:v1:en (accessed Apr. 11, 2020).

[96] M. Mao, P. Jin, N. D. Hatziargyriou, and L. Chang, “Multiagent-based hybrid energy management system for microgrids,” *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 938–946, 2014, doi: 10.1109/TSTE.2014.2313882.

[97] N. Blaauwbroek, P. H. Nguyen, M. J. Konsman, H. Shi, R. I. G. Kamphuis, and W. L. Kling, “Decentralized Resource Allocation and Load Scheduling for Multicommodity Smart Energy Systems,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1506–1514, Oct. 2015, doi: 10.1109/TSTE.2015.2441107.

[98] T. Jokela, M. Siponen, N. Hirasawa, and J. Earthy, “A survey of usability capability maturity models: Implications for practice and research,” *Behaviour and Information Technology*, vol. 25, no. 3. Taylor & Francis , pp. 263–282, May 01, 2006, doi: 10.1080/01449290500168079.

[99] M. S. Krishnan, C. H. Kriebel, S. Kekre, and T. Mukhopadhyay, “An Empirical Analysis of Productivity and Quality in Software Products,” *Management Science*, vol. 46. INFORMS, pp. 745–759, doi: 10.2307/2661483.

[100] T. Fawcett and S. Hampton, “Why & how energy efficiency policy should address SMEs,” *Energy Policy*, vol. 140, p. 111337, May 2020, doi: 10.1016/j.enpol.2020.111337.

[101] M. Pye and A. McKane, “Making a stronger case for industrial energy efficiency by quantifying non-energy benefits,” *Resour. Conserv. Recycl.*, vol. 28, no. 3–4, pp. 171–183, Feb. 2000, doi: 10.1016/S0921-3449(99)00042-7.

[102] L. A. Skumatz and J. Gardner, “Methods and results for measuring non-energy benefits in the

commercial and industrial sectors," in *Proceedings ACEEE Summer Study on Energy Efficiency in Industry*, 2005, no. 1, pp. 163–176, [Online]. Available: https://www.aceee.org/files/proceedings/2005/data/index.htm.

[103] E. Mills and A. Rosenfeld, "Consumer non-energy benefits as a motivation for making energy-efficiency improvements," *Energy*, vol. 21, no. 7–8, pp. 707–720, Jul. 1996, doi: 10.1016/0360-5442(96)00005-9.

[104] A. Gilchrist, *Industrial Internet Use-Cases*. Berkeley, CA: Apress, 2016.

[105] G. L. Tortorella and D. Fettermann, "Implementation of industry 4.0 and lean production in brazilian manufacturing companies," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2975–2987, Oct. 2018, doi: 10.1080/00207543.2017.1391420.

[106] T. Fleiter, E. Worrell, and W. Eichhammer, "Barriers to energy efficiency in industrial bottom-up energy demand models - A review," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 6. Pergamon, pp. 3099–3111, Aug. 01, 2011, doi: 10.1016/j.rser.2011.03.025.

[107] C. Walsh and P. Thornley, "Barriers to improving energy efficiency within the process industries with a focus on low grade heat utilisation," *J. Clean. Prod.*, vol. 23, no. 1, pp. 138–146, Mar. 2012, doi: 10.1016/j.jclepro.2011.10.038.

[108] H. L. F. de Groot, E. T. Verhoef, and P. Nijkamp, "Energy saving by firms: decision-making, barriers and policies," *Energy Econ.*, vol. 23, no. 6, pp. 717–740, Nov. 2001, doi: 10.1016/S0140-9883(01)00083-4.

[109] J. Harris, J. Anderson, and W. Shafron, "Investment in energy efficiency: A survey of Australian firms," *Energy Policy*, vol. 28, no. 12, pp. 867–876, Oct. 2000, doi: 10.1016/S0301-4215(00)00075-6.

[110] S. R. Hossain, I. Ahmed, F. S. Azad, and A. S. M. Monjurul Hasan, "Empirical investigation of energy management practices in cement industries of Bangladesh," *Energy*, vol. 212, p. 118741, Dec. 2020, doi: 10.1016/j.energy.2020.118741.

[111] M. A. Moktadir, T. Rahman, M. H. Rahman, S. M. Ali, and S. K. Paul, "Drivers to sustainable manufacturing practices and circular economy: A perspective of leather industries in Bangladesh," *J. Clean. Prod.*, vol. 174, pp. 1366–1380, Jan. 2018, doi: 10.1016/j.jclepro.2017.11.063.

[112] A. S. M. M. Hasan, M. A. Kabir, M. T. Hoq, M. T. Johansson, and P. Thollander, "Drivers and barriers to the implementation of biogas technologies in Bangladesh," *Biofuels*, pp. 1–13, Nov. 2020, doi: 10.1080/17597269.2020.1841362.

[113] "Bangladesh Power Development Board," 2020. https://www.bpdb.gov.bd/bpdb_new/index.php/site/area_wise_demand (accessed May 14, 2020).

[114] M. A. Habib, M. Hasanuzzaman, M. Hosenuzzaman, A. Salman, and M. R. Mehadi, "Energy consumption, energy saving and emission reduction of a garment industrial building in

Bangladesh," *Energy*, vol. 112, pp. 91–100, Oct. 2016, doi: 10.1016/j.energy.2016.06.062.

[115] H. P. Bedi, "'Our energy, our rights': National extraction legacies and contested energy justice futures in Bangladesh," *Energy Res. Soc. Sci.*, vol. 41, pp. 168–175, Jul. 2018, doi: 10.1016/j.erss.2018.04.009.

[116] P. Rohdin, P. Thollander, and P. Solding, "Barriers to and drivers for energy efficiency in the Swedish foundry industry," *Energy Policy*, vol. 35, no. 1, pp. 672–677, Jan. 2007, doi: 10.1016/j.enpol.2006.01.010.

[117] H. Hosseinzadeh-Bandbafha, A. Nabavi-Pelesaraei, M. Khanali, M. Ghahderijani, and K. wing Chau, "Application of data envelopment analysis approach for optimization of energy use and reduction of greenhouse gas emission in peanut production of Iran," *J. Clean. Prod.*, vol. 172, pp. 1327–1335, Jan. 2018, doi: 10.1016/j.jclepro.2017.10.282.

[118] W. Ouyang and J. bo Yang, "The network energy and environment efficiency analysis of 27 OECD countries: A multiplicative network DEA model," *Energy*, vol. 197, p. 117161, Apr. 2020, doi: 10.1016/j.energy.2020.117161.

[119] P. Thollander, I. L. Svensson, and L. Trygg, "Analyzing variables for district heating collaborations between energy utilities and industries," *Energy*, vol. 35, no. 9, pp. 3649–3656, Sep. 2010, doi: 10.1016/j.energy.2010.05.009.

[120] Danish, J. Zhang, B. Wang, and Z. Latif, "Towards cross-regional sustainable development: The nexus between information and communication technology, energy consumption, and <scp>CO</scp> $_2$ emissions," *Sustain. Dev.*, vol. 27, no. 5, pp. 990–1000, Sep. 2019, doi: 10.1002/sd.2000.

[121] E. Cagno and A. Trianni, "Evaluating the barriers to specific industrial energy efficiency measures: An exploratory study in small and medium-sized enterprises," *J. Clean. Prod.*, vol. 82, pp. 70–83, Nov. 2014, doi: 10.1016/j.jclepro.2014.06.057.

[122] E. Cagno, A. Trianni, C. Abeelen, E. Worrell, and F. Miggiano, "Barriers and drivers for energy efficiency: Different perspectives from an exploratory study in the Netherlands," *Energy Convers. Manag.*, vol. 102, pp. 26–38, Sep. 2015, doi: 10.1016/j.enconman.2015.04.018.

[123] C. Cooremans and A. Schönenberger, "Energy management: A key driver of energy-efficiency investment?," *J. Clean. Prod.*, vol. 230, pp. 264–275, 2019, doi: 10.1016/j.jclepro.2019.04.333.

[124] A. Lawrence, T. Nehler, E. Andersson, M. Karlsson, and P. Thollander, "Drivers, barriers and success factors for energy management in the Swedish pulp and paper industry," *J. Clean. Prod.*, vol. 223, pp. 67–82, Jun. 2019, doi: 10.1016/j.jclepro.2019.03.143.

[125] S. Z. Abbas, A. Kousar, S. Razzaq, A. Saeed, M. Alam, and A. Mahmood, "Energy management in South Asia," *Energy Strategy Reviews*, vol. 21. Elsevier Ltd, pp. 25–34, Aug. 01, 2018, doi: 10.1016/j.esr.2018.04.004.

[126] P. Thollander, M. Karlsson, P. Rohdin, J. Wollin, and J. Rosenqvist, "Energy management," in *Introduction to Industrial Energy Efficiency*, First Edit., Elsevier, 2020, pp. 239–257.

[127] K. Fujisaki, “Energy Management in Industry,” *J. Inst. Electr. Eng. Japan*, vol. 133, no. 12, pp. 821–824, 2013, doi: 10.1541/ieejjournal.133.821.

[128] E. Cagno, A. Neri, and A. Trianni, “Broadening to sustainability the perspective of industrial decision-makers on the energy efficiency measures adoption: some empirical evidence,” *Energy Effic.*, vol. 11, no. 5, pp. 1193–1210, Jun. 2018, doi: 10.1007/s12053-018-9621-0.

[129] A. Lawrence, P. Thollander, M. Andrei, and M. Karlsson, “Specific Energy Consumption/Use (SEC) in Energy Management for Improving Energy Efficiency in Industry: Meaning, Usage and Differences,” *Energies*, vol. 12, no. 2, p. 247, Jan. 2019, doi: 10.3390/en12020247.

[130] A. Lawrence, M. Karlsson, and P. Thollander, “Effects of firm characteristics and energy management for improving energy efficiency in the pulp and paper industry,” *Energy*, vol. 153, pp. 825–835, Jun. 2018, doi: 10.1016/j.energy.2018.04.092.

[131] Sandra Backlund; Sarah Broberg; Mikael Ottosson; Patrik Thollander., “Energy efficiency potentials and energy management practices in Swedish firms,” in *ECEEE Summer Study on Energy Efficiency in Industry*, 2012, pp. 669–677, Accessed: Sep. 28, 2020. [Online]. Available: https://www.eceee.org/library/conference_proceedings/eceee_Industrial_Summer_Study/2012/5-the-role-of-energy-management-systems-education-outreach-and-training/energy-efficiency-potentials-and-energy-management-practices-in-swedish-firms/.

[132] L. Sivill, J. Manninen, I. Hippinen, and P. Ahtila, “Success factors of energy management in energy-intensive industries: Development priority of energy performance measurement,” *Int. J. Energy Res.*, vol. 37, no. 8, pp. 936–951, Jun. 2013, doi: 10.1002/er.2898.

[133] A. Lawrence, P. Thollander, and M. Karlsson, “Drivers, Barriers, and Success Factors for Improving Energy Management in the Pulp and Paper Industry,” *Sustainability*, vol. 10, no. 6, p. 1851, Jun. 2018, doi: 10.3390/su10061851.

[134] A. Sannö, M. T. Johansson, P. Thollander, J. Wollin, and B. Sjögren, “Approaching Sustainable Energy Management Operations in a Multinational Industrial Corporation,” *Sustainability*, vol. 11, no. 3, p. 754, Jan. 2019, doi: 10.3390/su11030754.

[135] E. Andersson and P. Thollander, “Key performance indicators for energy management in the Swedish pulp and paper industry,” *Energy Strateg. Rev.*, vol. 24, pp. 229–235, Apr. 2019, doi: 10.1016/j.esr.2019.03.004.

[136] E. Cagno and A. Trianni, “Exploring drivers for energy efficiency within small- and medium-sized enterprises: First evidences from Italian manufacturing enterprises,” *Appl. Energy*, vol. 104, pp. 276–285, Apr. 2013, doi: 10.1016/j.apenergy.2012.10.053.

[137] M. T. Johansson and P. Thollander, “A review of barriers to and driving forces for improved energy efficiency in Swedish industry– Recommendations for successful in-house energy management,” *Renewable and Sustainable Energy Reviews*, vol. 82. Elsevier Ltd, pp. 618–628, Feb. 01, 2018, doi: 10.1016/j.rser.2017.09.052.

[138] P. Thollander and M. Ottosson, “An energy efficient Swedish pulp and paper industry -

Exploring barriers to and driving forces for cost-effective energy efficiency investments," *Energy Effic.*, vol. 1, no. 1, pp. 21–34, Jan. 2008, doi: 10.1007/s12053-007-9001-7.

[139] "Bangladesh Overview." https://www.worldbank.org/en/country/bangladesh/overview (accessed Jul. 06, 2020).

[140] E. Vine, "An international survey of the energy service company ESCO industry," *Energy Policy*, vol. 33, no. 5, pp. 691–704, Mar. 2005, doi: 10.1016/j.enpol.2003.09.014.

[141] N. Okay and U. Akman, "Analysis of ESCO activities using country indicators," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9. Elsevier Ltd, pp. 2760–2771, Dec. 01, 2010, doi: 10.1016/j.rser.2010.07.013.

[142] J. P. Carvallo, S. P. Murphy, E. Stuart, P. H. Larsen, and C. Goldman, "Evaluating project level investment trends for the U.S. ESCO industry: 1990–2017," *Energy Policy*, vol. 130, pp. 139–161, Jul. 2019, doi: 10.1016/j.enpol.2019.03.061.

[143] S. Bobbino, H. Galván, and M. González-Eguino, "Budget-neutral financing to unlock energy savings potential: An analysis of the ESCO model in Barcelona," in *Green Energy and Technology*, vol. 164, Springer Verlag, 2015, pp. 183–199.

[144] Nurcahyanto, Y. Simsek, and T. Urmee, "Opportunities and challenges of energy service companies to promote energy efficiency programs in Indonesia," *Energy*, vol. 205, p. 117603, May 2020, doi: 10.1016/j.energy.2020.117603.

[145] P. Bertoldi, S. Rezessy, and E. Vine, "Energy service companies in European countries: Current status and a strategy to foster their development," *Energy Policy*, vol. 34, no. 14, pp. 1818–1832, Sep. 2006, doi: 10.1016/j.enpol.2005.01.010.

[146] E. L. Vine, C. Murakoshi, and H. Nakagami, "International ESCO business opportunities and challenges: A Japanese case study," *Energy*, vol. 23, no. 6, pp. 439–447, Jun. 1998, doi: 10.1016/S0360-5442(98)00008-5.

[147] Chiharu Murakoshi; Hidetoshi Nakagami, "Current state of ESCO activities in Asia: ESCO industry development programs and future tasks in Asian countries," in *ACEEE Summer Studies on Energy Efficiency in Industry*, 2009, pp. 311–322, Accessed: Jun. 28, 2020. [Online]. Available: https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2009/Panel_2/2.057/.

[148] R. K. Yin, *Case Study Research: Design and Methods*, Fourth Edi. SAGE Publications, Inc., 2009.

[149] N. Siggelkow, "Persuasion with case studies," *Acad. Manag. J.*, vol. 50, no. 1, pp. 20–24, Feb. 2007, doi: 10.5465/AMJ.2007.24160882.

[150] M. . Patton, *Qualitative Evaluation and Research Methods*, Second edi. Newbury Park, California: SAGE, 1990.

[151] "Sustainable & Renewable Energy Development Authority (SREDA)."

http://www.sreda.gov.bd/index.php/site/page/82ea-5f0f-bc13-4c81-3875-61c7-1a3d-abe5-7b58-5ac2 (accessed May 14, 2020).

[152] H. C. W. de Vet, L. B. Mokkink, D. G. Mosmuller, and C. B. Terwee, "Spearman–Brown prophecy formula and Cronbach's alpha: different faces of reliability and opportunities for new applications," *J. Clin. Epidemiol.*, vol. 85, pp. 45–49, May 2017, doi: 10.1016/j.jclinepi.2017.01.013.

[153] A. Christmann and S. Van Aelst, "Robust estimation of Cronbach's alpha," *J. Multivar. Anal.*, vol. 97, no. 7, pp. 1660–1674, Aug. 2006, doi: 10.1016/j.jmva.2005.05.012.

[154] E. B. Martin and A. Julian Morris, "Taking Multivariate Statistics out into Industry — Multivariate Statistical Progress Control and Process Performance Monitoring," 1997, pp. 51–64.

[155] H. Toutenburg and Shalabh, "Comparison of Two Samples," 2009, pp. 21–43.

[156] A. Hasanbeigi, C. Menke, and P. du Pont, "Barriers to energy efficiency improvement and decision-making behavior in Thai industry," *Energy Effic.*, vol. 3, no. 1, pp. 33–52, Jan. 2010, doi: 10.1007/s12053-009-9056-8.

[157] F. Backman, "Barriers to Energy Efficiency in Swedish Non-Energy-Intensive Micro- and Small-Sized Enterprises—A Case Study of a Local Energy Program," *Energies*, vol. 10, no. 1, p. 100, Jan. 2017, doi: 10.3390/en10010100.

[158] E. Andersson, O. Arfwidsson, V. Bergstrand, and P. Thollander, "A study of the comparability of energy audit program evaluations," *J. Clean. Prod.*, vol. 142, pp. 2133–2139, 2017, doi: 10.1016/j.jclepro.2016.11.070.

[159] J. Palm and P. Thollander, "An interdisciplinary perspective on industrial energy efficiency," *Appl. Energy*, vol. 87, no. 10, pp. 3255–3261, Oct. 2010, doi: 10.1016/j.apenergy.2010.04.019.

[160] R. Ciriminna, F. Meneguzzo, M. Pecoraino, and M. Pagliaro, "Reshaping the education of energy managers," *Energy Res. Soc. Sci.*, vol. 21, pp. 44–48, Nov. 2016, doi: 10.1016/j.erss.2016.06.022.

[161] P. Thollander, S. Backlund, A. Trianni, and E. Cagno, "Beyond barriers - A case study on driving forces for improved energy efficiency in the foundry industries in Finland, France, Germany, Italy, Poland, Spain, and Sweden," *Appl. Energy*, vol. 111, pp. 636–643, Nov. 2013, doi: 10.1016/j.apenergy.2013.05.036.

[162] D. V. Bush, "The Changing Role of the Energy Manager," *Strateg. Plan. Energy Environ.*, vol. 23, no. 2, pp. 31–39, 2003, doi: 10.1080/10485230309509636.

[163] C. Cooremans, "Make it strategic! Financial investment logic is not enough," *Energy Efficiency*, vol. 4, no. 4. Springer, pp. 473–492, Nov. 21, 2011, doi: 10.1007/s12053-011-9125-7.

[164] V. António da Silva Gonçalves and F. J. Mil-Homens dos Santos, "Energy management system ISO 50001:2011 and energy management for sustainable development," *Energy Policy*, vol. 133, p. 110868, Oct. 2019, doi: 10.1016/j.enpol.2019.07.004.

[165] J. M. Sousa Lira, E. G. Salgado, and L. A. Beijo, "Which factors does the diffusion of ISO 50001 in different regions of the world is influenced?," *J. Clean. Prod.*, vol. 226, pp. 759–767, Jul. 2019, doi: 10.1016/j.jclepro.2019.04.127.

[166] H. Kanneganti *et al.*, "Specification of energy assessment methodologies to satisfy ISO 50001 energy management standard," *Sustain. Energy Technol. Assessments*, vol. 23, pp. 121–135, 2017, doi: 10.1016/j.seta.2017.09.003.

[167] F. Marimon and M. Casadesús, "Reasons to Adopt ISO 50001 Energy Management System," *Sustainability*, vol. 9, no. 10, p. 1740, Sep. 2017, doi: 10.3390/su9101740.

[168] A. Trianni, E. Cagno, E. Worrell, and G. Pugliese, "Empirical investigation of energy efficiency barriers in Italian manufacturing SMEs," *Energy*, vol. 49, no. 1, pp. 444–458, Jan. 2013, doi: 10.1016/j.energy.2012.10.012.

[169] "Promoting Energy Efficiency in Bangladesh | Energy Efficiency Case Studies | U.S. Agency for International Development." https://www.usaid.gov/energy/efficiency/examples/bangladesh (accessed May 14, 2020).

[170] "Energy Efficiency and Energy Auditing in Bangladesh | Green Growth Knowledge Platform." https://www.greengrowthknowledge.org/resource/energy-efficiency-and-energy-auditing-bangladesh (accessed May 14, 2020).

[171] J. Malinauskaite, H. Jouhara, L. Ahmad, M. Milani, L. Montorsi, and M. Venturelli, "Energy efficiency in industry: EU and national policies in Italy and the UK," *Energy*, vol. 172, pp. 255–269, Apr. 2019, doi: 10.1016/j.energy.2019.01.130.

[172] S. S. Steve Sorrell, Eoin O'Malley, Joachim Schleich, *Reducing barriers to energy efficiency in private and public organisations. Final Report*. Sussex: Energy Research Centre-Science and Technology Policy Research (SPRU). Brighton: University of Sussex; 2000., 2000.

[173] N. Nagesha and P. Balachandra, "Barriers to energy efficiency in small industry clusters: Multi-criteria-based prioritization using the analytic hierarchy process," *Energy*, vol. 31, no. 12, pp. 1969–1983, Sep. 2006, doi: 10.1016/j.energy.2005.07.002.

[174] A. Trianni and E. Cagno, "Dealing with barriers to energy efficiency and SMEs: Some empirical evidences," *Energy*, vol. 37, no. 1, pp. 494–504, Jan. 2012, doi: 10.1016/j.energy.2011.11.005.

[175] Y. Fernando and W. L. Hor, "Impacts of energy management practices on energy efficiency and carbon emissions reduction: A survey of malaysian manufacturing firms," *Resour. Conserv. Recycl.*, vol. 126, pp. 62–73, Nov. 2017, doi: 10.1016/j.resconrec.2017.07.023.

[176] T. Fawcett and G. Killip, "Re-thinking energy efficiency in European policy: Practitioners' use of 'multiple benefits' arguments," *J. Clean. Prod.*, vol. 210, pp. 1171–1179, Feb. 2019, doi: 10.1016/j.jclepro.2018.11.026.

[177] C. Stenqvist and L. J. Nilsson, "Energy efficiency in energy-intensive industries—an evaluation of the Swedish voluntary agreement PFE," vol. 5, no. 2, pp. 225–241, 2012, doi: 10.1007/s12053-011-9131-9.

[178] S. Paramonova, P. Thollander, and M. Ottosson, “Quantifying the extended energy efficiency gap-evidence from Swedish electricity-intensive industries,” *Renewable and Sustainable Energy Reviews*, vol. 51. Elsevier Ltd, pp. 472–483, Jun. 29, 2015, doi: 10.1016/j.rser.2015.06.012.

[179] K.-H. Lee, “Drivers and Barriers to Energy Efficiency Management for Sustainable Development,” *Sustain. Dev.*, vol. 23, no. 1, pp. 16–25, Jan. 2015, doi: 10.1002/sd.1567.

[180] G. May, I. Barletta, B. Stahl, and M. Taisch, “Energy management in production: A novel method to develop key performance indicators for improving energy efficiency,” *Appl. Energy*, vol. 149, pp. 46–61, 2015, doi: 10.1016/j.apenergy.2015.03.065.

[181] “Tracking Industry 2020 – Analysis - IEA,” 2020. https://www.iea.org/reports/tracking-industry-2020 (accessed Nov. 18, 2021).

[182] “Multiple Benefits of Energy Efficiency – Analysis - IEA,” 2019. Accessed: Mar. 30, 2020. [Online]. Available: https://www.iea.org/reports/multiple-benefits-of-energy-efficiency.

[183] “Industry – Energy Efficiency 2020 – Analysis - IEA,” 2020. https://www.iea.org/reports/energy-efficiency-2020/industry (accessed Nov. 18, 2021).

[184] M. G. Patterson, “What is energy efficiency?: Concepts, indicators and methodological issues,” *Energy Policy*, vol. 24, no. 5, pp. 377–390, May 1996, doi: 10.1016/0301-4215(96)00017-1.

[185] N. N. Abu Bakar *et al.*, “Energy efficiency index as an indicator for measuring building energy performance: A review,” *Renew. Sustain. Energy Rev.*, vol. 44, pp. 1–11, Apr. 2015, doi: 10.1016/j.rser.2014.12.018.

[186] T. Xu, J. Flapper, and K. J. Kramer, “Characterization of energy use and performance of global cheese processing,” *Energy*, vol. 34, no. 11, pp. 1993–2000, Nov. 2009, doi: 10.1016/J.ENERGY.2009.08.014.

[187] S. Siitonen, M. Tuomaala, and P. Ahtila, “Variables affecting energy efficiency and CO2 emissions in the steel industry,” *Energy Policy*, vol. 38, no. 5, pp. 2477–2485, May 2010, doi: 10.1016/J.ENPOL.2009.12.042.

[188] E. Cagno, P. Trucco, A. Trianni, and G. Sala, “Quick-E-scan: A methodology for the energy scan of SMEs,” *Energy*, vol. 35, no. 5, pp. 1916–1926, 2010, doi: 10.1016/j.energy.2010.01.003.

[189] E. Worrell, L. Bernstein, J. Roy, L. Price, and J. Harnisch, “Industrial energy efficiency and climate change mitigation,” *Energy Effic.*, vol. 2, no. 2, pp. 109–123, 2009, doi: 10.1007/s12053-008-9032-8.

[190] “Energy - United Nations Sustainable Development.” https://www.un.org/sustainabledevelopment/energy/ (accessed Feb. 28, 2022).

[191] “Infrastructure and Industrialization - United Nations Sustainable Development.” https://www.un.org/sustainabledevelopment/infrastructure-industrialization/ (accessed Feb. 28, 2022).

[192] P. Thollander, M. Karlsson, P. Rohdin, J. Wollin, and J. Rosenqvist, “Barriers to energy

efficiency," in *Introduction to Industrial Energy Efficiency*, Elsevier, 2020, pp. 291–305.

[193] W. C. T. Stephan A. Roosa, Steve Doty, *Energy Management Handbook*, 9th Editio. Fairmont Press, 2018.

[194] L. A. Greening, D. L. Greene, and C. Difiglio, "Energy efficiency and consumption — the rebound effect — a survey," *Energy Policy*, vol. 28, no. 6–7, pp. 389–401, 2000, doi: 10.1016/s0301-4215(00)00021-5.

[195] M. J. Fell, "Energy services: A conceptual review," *Energy Res. Soc. Sci.*, vol. 27, pp. 129–140, 2017, doi: 10.1016/j.erss.2017.02.010.

[196] D. Kindström and M. Ottosson, "Local and regional energy companies offering energy services: Key activities and implications for the business model," *Appl. Energy*, vol. 171, pp. 491–500, Jun. 2016, doi: 10.1016/j.apenergy.2016.03.092.

[197] G. Kalt, D. Wiedenhofer, C. Görg, and H. Haberl, "Conceptualizing energy services: A review of energy and well-being along the Energy Service Cascade," *Energy Res. Soc. Sci.*, vol. 53, pp. 47–58, 2019, doi: 10.1016/j.erss.2019.02.026.

[198] W. H. Mashburn, "Effective Energy Management," in *Energy Management Handbook*, 9th ed., S. A. R. S. D. W. C. Turner;, Ed. Lilburn, GA, USA: The Fairmont Press, 2018, pp. 17–26.

[199] A. S. M. M. Hasan, R. A. Tuhin, M. Ullah, T. H. Sakib, P. Thollander, and A. Trianni, "A comprehensive investigation of energy management practices within energy intensive industries in Bangladesh," *Energy*, vol. 232, p. 120932, Oct. 2021, doi: 10.1016/j.energy.2021.120932.

[200] M. Ghobakhloo, "Industry 4.0, digitization, and opportunities for sustainability," *J. Clean. Prod.*, vol. 252, p. 119869, Apr. 2020, doi: 10.1016/j.jclepro.2019.119869.

[201] F. van H. V. L. B. Porter, Ed., *Handbook of Knowledge Representation*, First edit. Amsterdam, The Netherland: Elsevier Science, 2007.

[202] E. Cagno, D. Moschetta, and A. Trianni, "Only non-energy benefits from the adoption of energy efficiency measures? A novel framework," *J. Clean. Prod.*, vol. 212, pp. 1319–1333, Mar. 2019, doi: 10.1016/j.jclepro.2018.12.049.

[203] E. Worrell and G. Biermans, "Move over! Stock turnover, retrofit and industrial energy efficiency," *Energy Policy*, vol. 33, no. 7, pp. 949–962, May 2005, doi: 10.1016/j.enpol.2003.10.017.

[204] P. Sandberg and M. Söderström, "Industrial energy efficiency: The need for investment decision support from a manager perspective," *Energy Policy*, vol. 31, no. 15, pp. 1623–1634, Dec. 2003, doi: 10.1016/S0301-4215(02)00228-8.

[205] D. Wulfinghoff, *Energy efficiency manual : for everyone who uses energy, pays for utilities, controls energy usage, designs and builds, is interested in energy and environmental preservation*. Energy Institute Press, 1999.

[206] S. Eilon, "Definition and effect of productivity on corporate performance," *Omega*, vol. 15, no. 5, pp. 389–393, 1987, doi: 10.1016/0305-0483(87)90039-9.

[207] X. Wen, H. Cao, B. Hon, E. Chen, and H. Li, "Energy value mapping: A novel lean method to integrate energy efficiency into production management," *Energy*, vol. 217, p. 119353, 2021, doi: 10.1016/j.energy.2020.119353.

[208] L. Smith and P. Ball, "Steps towards sustainable manufacturing through modelling material, energy and waste flows," *Int. J. Prod. Econ.*, vol. 140, no. 1, pp. 227–238, 2012, doi: 10.1016/j.ijpe.2012.01.036.

[209] E. Giacone and S. Mancò, "Energy efficiency measurement in industrial processes," *Energy*, vol. 38, no. 1, pp. 331–345, 2012, doi: 10.1016/j.energy.2011.11.054.

[210] M. Braglia, D. Castellano, R. Gabbrielli, and L. Marrazzini, "Energy Cost Deployment (ECD): A novel lean approach to tackling energy losses," *J. Clean. Prod.*, vol. 246, p. 119056, Feb. 2020, doi: 10.1016/j.jclepro.2019.119056.

[211] A. Almeida and J. Cunha, "The implementation of an Activity-Based Costing (ABC) system in a manufacturing company," *Procedia Manuf.*, vol. 13, pp. 932–939, Jan. 2017, doi: 10.1016/j.promfg.2017.09.162.

[212] M. Barth, A. Livet, and R. De Guio, "Effective activity-based costing for manufacturing enterprises using a shop floor reference model," *Int. J. Prod. Res.*, vol. 46, no. 3, pp. 621–646, 2008, doi: 10.1080/00207540600845750.

[213] T. Nehler, "A Systematic Literature Review of Methods for Improved Utilisation of the Non-Energy Benefits of Industrial Energy Efficiency," *Energies*, vol. 11, no. 12, p. 3241, Nov. 2018, doi: 10.3390/en11123241.

[214] C. K. Bhat, D. Kaul, G. S. Lodha, R. Koul, and K. J. S. Sawhney, "Wear and tear studies of oil-lubricated machines using energy-dispersive X-ray fluorescence spectrometry," *X-Ray Spectrom.*, vol. 18, no. 5, pp. 243–245, Oct. 1989, doi: 10.1002/xrs.1300180512.

[215] P. Stavropoulos, D. Chantzis, C. Doukas, A. Papacharalampopoulos, and G. Chryssolouris, "Monitoring and Control of Manufacturing Processes: A Review," *Procedia CIRP*, vol. 8, pp. 421–425, 2013, doi: 10.1016/j.procir.2013.06.127.

[216] P. Palensky and D. Dietrich, "Demand side management: Demand response, intelligent energy systems, and smart loads," *IEEE Trans. Ind. Informatics*, vol. 7, no. 3, pp. 381–388, Aug. 2011, doi: 10.1109/TII.2011.2158841.

[217] U. Bac, K. A. M. S. Alaloosi, and C. Turhan, "A comprehensive evaluation of the most suitable HVAC system for an industrial building by using a hybrid building energy simulation and multi criteria decision making framework," *J. Build. Eng.*, vol. 37, p. 102153, May 2021, doi: 10.1016/j.jobe.2021.102153.

[218] N. R. Gayam and K. Shanmuganandam, "Investigation on industrial layouts: Modifications by a varied approach," *Mater. Today Proc.*, Nov. 2020, doi: 10.1016/j.matpr.2020.10.275.

[219] S. Tappura, N. Nenonen, and J. Kivistö-Rahnasto, "Managers' viewpoint on factors influencing their commitment to safety: An empirical investigation in five Finnish industrial organisations,"

*Saf. Sci.*, vol. 96, pp. 52–61, 2017, doi: 10.1016/j.ssci.2017.03.007.

[220] A. Brall, "Availability modeling for the application of manufacturing equipment," doi: 10.1109/rams.2002.981676.

[221] T. Sueyoshi and M. Goto, "Resource utilization for sustainability enhancement in Japanese industries," *Appl. Energy*, vol. 228, pp. 2308–2320, Oct. 2018, doi: 10.1016/J.APENERGY.2018.07.031.

[222] D. J. Johnson, "A framework for reducing manufacturing throughput time," *J. Manuf. Syst.*, vol. 22, no. 4, pp. 283–298, Jan. 2003, doi: 10.1016/S0278-6125(03)80009-2.

[223] J. Miltenburg and D. Sparling, "Managing and reducing total cycle time: models and analysis," *Int. J. Prod. Econ.*, vol. 46–47, pp. 89–108, 1996, doi: 10.1016/0925-5273(94)00084-0.

[224] "Energy Service Companies (ESCOs) | E3P." https://e3p.jrc.ec.europa.eu/communities/energy-service-companies (accessed Jan. 30, 2021).

[225] S. Panev, N. Labanca, P. Bertoldi, T. Serrenho, C. Cahill, and B. B. Kiss, "ESCO market report for non-European countries 2013," *JRC Science and Policy Report*. pp. 12–18, 2014, doi: 10.2790/005265.

[226] K. L. Soroye and L. J. Nilsson, "Building a business to close the efficiency gap: the Swedish ESCO Experience," *Energy Effic.*, vol. 3, no. 3, pp. 237–256, 2010, doi: 10.1007/s12053-009-9069-3.

[227] B. Duplessis, J. Ô. Adnot, M. Dupont, and F. Racapé, "An empirical typology of energy services based on a well-developed market: France," *Energy Policy*, vol. 45, pp. 268–276, Jun. 2012, doi: 10.1016/j.enpol.2012.02.031.

[228] X. Liu, R. Yamamoto, and S. Suk, "A survey analysis of energy saving activities of industrial companies in Hyogo, Japan," *J. Clean. Prod.*, vol. 66, pp. 288–300, Mar. 2014, doi: 10.1016/j.jclepro.2013.10.011.

[229] X. Liu, D. Niu, C. Bao, S. Suk, and T. Shishime, "A survey study of energy saving activities of industrial companies in Taicang, China," *J. Clean. Prod.*, vol. 26, pp. 79–89, May 2012, doi: 10.1016/j.jclepro.2011.12.030.

[230] T. Nehler, "Linking energy efficiency measures in industrial compressed air systems with non-energy benefits – A review," *Renewable and Sustainable Energy Reviews*, vol. 89. Elsevier Ltd, pp. 72–87, Jun. 01, 2018, doi: 10.1016/j.rser.2018.02.018.

[231] S. Darby, "Making sense of energy advice," in *ECEEE Summer Study proceedings*, 2003, pp. 1217–1226, Accessed: Apr. 26, 2021. [Online]. Available: https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2003/Panel_6/6157darby/.

[232] J. Fresner, F. Morea, C. Krenn, J. Aranda Uson, and F. Tomasi, "Energy efficiency in small and medium enterprises: Lessons learned from 280 energy audits across Europe," *J. Clean. Prod.*, vol. 142, pp. 1650–1660, 2017, doi: 10.1016/j.jclepro.2016.11.126.

[233] T. Fleiter, J. Schleich, and P. Ravivanpong, “Adoption of energy-efficiency measures in SMEs—An empirical analysis based on energy audit data from Germany,” *Energy Policy*, vol. 51, pp. 863–875, 2012, doi: 10.1016/j.enpol.2012.09.041.

[234] M. Jakob, “Marginal costs and co-benefits of energy efficiency investments. The case of the Swiss residential sector,” *Energy Policy*, vol. 34, no. 2 SPEC. ISS., pp. 172–187, Jan. 2006, doi: 10.1016/j.enpol.2004.08.039.

[235] S. Sorrell, J. Dimitropoulos, and M. Sommerville, “Empirical estimates of the direct rebound effect: A review,” *Energy Policy*, vol. 37, no. 4, pp. 1356–1371, 2009, doi: 10.1016/j.enpol.2008.11.026.

[236] M. I. Howells, T. Alfstad, D. G. Victor, G. Goldstein, and U. Remme, “A model of household energy services in a low-income rural African village,” *Energy Policy*, vol. 33, no. 14, pp. 1833–1851, 2005, doi: 10.1016/j.enpol.2004.02.019.

[237] D. B. Reister and W. D. Devine, “Total costs of energy services,” *Energy*, vol. 6, no. 4, pp. 305–315, 1981, doi: 10.1016/0360-5442(81)90074-8.

[238] N. Supersberger, S. Lechtenböhmer, and D. Seifried, “The role of energy efficiency in the development of the Iranian energy system – energy scenario analysis,” in *ECEEE Summer Study proceedings*, 2009, pp. 51–62, [Online]. Available: https://www.eceee.org/static/media/uploads/site-2/library/conference_proceedings/eceee_Summer_Studies/2009/Panel_1/1.060/paper.pdf.

[239] J. Ouyang and H. Shen, “The choice of energy saving modes for an energy-intensive manufacturer considering non-energy benefits,” *J. Clean. Prod.*, vol. 141, pp. 83–98, 2017, doi: 10.1016/j.jclepro.2016.08.142.

[240] N. Finnerty, R. Sterling, S. Contreras, D. Coakley, and M. M. Keane, “Defining corporate energy policy and strategy to achieve carbon emissions reduction targets via energy management in non-energy intensive multi-site manufacturing organisations,” *Energy*, vol. 151, pp. 913–929, 2018, doi: 10.1016/j.energy.2018.03.070.

[241] Pierre Langlois; Shirley J. Hansen, *World ESCO Outlook*, 1st Editio. The Fairmont Press, 2012.

[242] E. Mills *et al.*, “The business case for energy management in high-tech industries,” *Energy Effic.*, vol. 1, no. 1, pp. 5–20, Jan. 2008, doi: 10.1007/s12053-007-9000-8.

[243] M. A. Paula Pinheiro, D. Jugend, L. C. Demattê Filho, and F. Armellini, “Framework proposal for ecodesign integration on product portfolio management,” *J. Clean. Prod.*, vol. 185, pp. 176–186, Jun. 2018, doi: 10.1016/j.jclepro.2018.03.005.

[244] R. Martin, M. Muûls, L. B. De Preux, and U. J. Wagner, “Anatomy of a paradox: Management practices, organizational structure and energy efficiency,” *J. Environ. Econ. Manage.*, vol. 63, no. 2, pp. 208–223, Mar. 2012, doi: 10.1016/j.jeem.2011.08.003.

[245] A. Trianni, E. Cagno, and E. Worrell, “Innovation and adoption of energy efficient technologies: An exploratory analysis of Italian primary metal manufacturing SMEs,” *Energy Policy*, vol. 61,

pp. 430–440, Oct. 2013, doi: 10.1016/j.enpol.2013.06.034.

[246] D. H. W. Li and E. K. W. Tsang, “An analysis of daylighting performance for office buildings in Hong Kong,” *Build. Environ.*, vol. 43, no. 9, pp. 1446–1458, Sep. 2008, doi: 10.1016/j.buildenv.2007.07.002.

[247] T. Leephakpreeda, “Adaptive occupancy-based lighting control via Grey prediction,” *Build. Environ.*, vol. 40, no. 7, pp. 881–886, Jul. 2005, doi: 10.1016/j.buildenv.2004.08.026.

[248] J. C. Van Gorp, “Enterprising energy management,” *IEEE Power Energy Mag.*, vol. 2, no. 1, pp. 59–63, 2004, doi: 10.1109/mpae.2004.1263421.

[249] A. Marino, P. Bertoldi, S. Rezessy, and B. Boza-Kiss, “A snapshot of the European energy service market in 2010 and policy recommendations to foster a further market development,” *Energy Policy*, vol. 39, no. 10, pp. 6190–6198, 2011, doi: 10.1016/j.enpol.2011.07.019.

[250] P. Thollander, P. Rohdin, B. Moshfegh, M. Karlsson, M. Söderström, and L. Trygg, “Energy in Swedish industry 2020 - Current status, policy instruments, and policy implications,” *J. Clean. Prod.*, vol. 51, pp. 109–117, Jul. 2013, doi: 10.1016/j.jclepro.2013.01.021.

[251] C Caffal, *Energy management in industry*. Sittard, the Netherlands: Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET), 1995.

[252] C. Dieperink, I. Brand, and W. Vermeulen, “Diffusion of energy-saving innovations in industry and the built environment: Dutch studies as inputs for a more integrated analytical framework,” *Energy Policy*, vol. 32, no. 6, pp. 773–784, 2004, doi: 10.1016/s0301-4215(02)00341-5.

[253] D. L. Norland and L. Lind, “Corporate energy management: A survey of large manufacturing companies,” *Energy Eng.*, vol. 98, no. 2, pp. 53–72, 2001, doi: 10.1080/01998590109509308.

[254] F. Shrouf, J. Ordieres, and G. Miragliotta, “Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm,” in *IEEE International Conference on Industrial Engineering and Engineering Management*, 2014, vol. 2015-Janua, pp. 697–701, doi: 10.1109/IEEM.2014.7058728.

[255] D. Ramin, S. Spinelli, and A. Brusaferri, “Demand-side management via optimal production scheduling in power-intensive industries: The case of metal casting process,” *Appl. Energy*, vol. 225, pp. 622–636, Sep. 2018, doi: 10.1016/j.apenergy.2018.03.084.

[256] C. Voss, N. Tsikriktsis, and M. Frohlich, “Case research in operations management,” *Int. J. Oper. Prod. Manag.*, vol. 22, no. 2, pp. 195–219, 2002, doi: 10.1108/01443570210414329/FULL/XML.

[257] K. M. Eisenhardt, “Building Theories from Case Study Research,” *https://doi.org/10.5465/amr.1989.4308385*, vol. 8, no. 4, pp. 2–12, Oct. 1989, doi: 10.5465/AMR.1989.4308385.

[258] M. Pagell and D. Gobeli, “How Plant Managers’ Experiences and Attitudes Toward Sustainability Relate to Operational Performance,” *Prod. Oper. Manag.*, vol. 18, no. 3, pp. 278–299, May 2009, doi: 10.1111/J.1937-5956.2009.01050.X.

[259] J. Cho and A. Trent, "Validity in qualitative research revisited," *Qual. Res.*, vol. 6, no. 3, pp. 319–340, Nov. 2006, doi: 10.1177/1468794106065006.

[260] P. Singh, C. Carliell-Marquet, and A. Kansal, "Energy pattern analysis of a wastewater treatment plant," *Appl. Water Sci. 2012 23*, vol. 2, no. 3, pp. 221–226, May 2012, doi: 10.1007/S13201-012-0040-7.

[261] R. Negi and M. K. Chandel, "Analysing water-energy-GHG nexus in a wastewater treatment plant of Mumbai Metropolitan Region, India," *Environ. Res.*, vol. 196, p. 110931, May 2021, doi: 10.1016/j.envres.2021.110931.

[262] S. Jeschke, C. Brecher, T. Meisen, D. Özdemir, and T. Eschert, "Industrial Internet of Things and Cyber Manufacturing Systems," Springer, Cham, 2017, pp. 3–19.

[263] B. Zhou, Y. Qi, and Y. Liu, "Proactive preventive maintenance policy for buffered serial production systems based on energy saving opportunistic windows," *J. Clean. Prod.*, vol. 253, p. 119791, Apr. 2020, doi: 10.1016/J.JCLEPRO.2019.119791.

[264] J. R. Duflou *et al.*, "Towards energy and resource efficient manufacturing: A processes and systems approach," *CIRP Ann. - Manuf. Technol.*, vol. 61, no. 2, pp. 587–609, Jan. 2012, doi: 10.1016/j.cirp.2012.05.002.

[265] F. Alhourani and U. Saxena, "Factors affecting the implementation rates of energy and productivity recommendations in small and medium sized companies," *J. Manuf. Syst.*, vol. 28, no. 1, pp. 41–45, Jan. 2009, doi: 10.1016/J.JMSY.2009.04.001.

[266] D. A. Garcia, F. Cumo, M. Tiberi, V. Sforzini, and G. Piras, "Cost-Benefit Analysis for Energy Management in Public Buildings: Four Italian Case Studies," *Energies 2016, Vol. 9, Page 522*, vol. 9, no. 7, p. 522, Jul. 2016, doi: 10.3390/EN9070522.

[267] T. Söderqvist, P. Brinkhoff, T. Norberg, L. Rosén, P. E. Back, and J. Norrman, "Cost-benefit analysis as a part of sustainability assessment of remediation alternatives for contaminated land," *J. Environ. Manage.*, vol. 157, pp. 267–278, Jul. 2015, doi: 10.1016/J.JENVMAN.2015.04.024.

[268] P. Thollander, M. Karlsson, P. Rohdin, J. Wollin, and J. Rosenqvist, "Energy efficiency gap," in *Introduction to Industrial Energy Efficiency*, First., Elsevier, 2020, p. 31.

[269] M. Ghobakhloo, "The future of manufacturing industry: a strategic roadmap toward Industry 4.0," *J. Manuf. Technol. Manag.*, vol. 29, no. 6, pp. 910–936, 2018, doi: 10.1108/jmtm-02-2018-0057.

[270] J. Xu, C. Zhao, F. Wang, and G. Yang, "Industrial decarbonisation oriented distributed renewable generation towards wastewater treatment sector: Case from the Yangtze River Delta region in China," *Energy*, p. 124562, Jun. 2022, doi: 10.1016/J.ENERGY.2022.124562.

[271] T. Zheng, M. Ardolino, A. Bacchetti, and M. Perona, "The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review," *Int. J. Prod. Res.*, vol. 59, no. 6, pp. 1922–1954, 2021, doi: 10.1080/00207543.2020.1824085.

[272] V. Alcácer and V. Cruz-Machado, "Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems," *Eng. Sci. Technol. an Int. J.*, vol. 22, no. 3, pp. 899–919, Jun. 2019, doi: 10.1016/j.jestch.2019.01.006.

[273] W. Yu, P. Patros, B. Young, E. Klinac, and T. G. Walmsley, "Energy digital twin technology for industrial energy management: Classification, challenges and future," *Renew. Sustain. Energy Rev.*, vol. 161, p. 112407, Jun. 2022, doi: 10.1016/J.RSER.2022.112407.

[274] S. Nimbalkar, S. D. Supekar, W. Meadows, T. Wenning, W. Guo, and J. Cresko, "Enhancing operational performance and productivity benefits in breweries through smart manufacturing technologies," *J. Adv. Manuf. Process.*, vol. 2, no. 4, p. e10064, Oct. 2020, doi: 10.1002/AMP2.10064.

[275] M. C. Jena, S. K. Mishra, and H. S. Moharana, "Application of Industry 4.0 to enhance sustainable manufacturing," *Environ. Prog. Sustain. Energy*, vol. 39, no. 1, p. 13360, Jan. 2020, doi: 10.1002/EP.13360.

[276] I. Laskurain-Iturbe, G. Arana-Landin, B. Landeta-Manzano, and R. Jimenez-Redal, "Assessing the uptake of Industry 4.0 technologies: barriers to their adoption and impact on quality management aspects," *Int. J. Qual. Reliab. Manag.*, 2023, doi: 10.1108/ijqrm-10-2022-0292.

[277] L. S. Dalenogare, G. B. Benitez, N. F. Ayala, and A. G. Frank, "The expected contribution of Industry 4.0 technologies for industrial performance," *Int. J. Prod. Econ.*, vol. 204, pp. 383–394, Oct. 2018, doi: 10.1016/j.ijpe.2018.08.019.

[278] S. Ali and Y. Xie, "The impact of Industry 4.0 on organizational performance: the case of Pakistan's retail industry," *Eur. J. Manag. Stud.*, 2021, doi: 10.1108/ejms-01-2021-0009.

[279] P. P. Poveda-Orjuela, J. C. García-Díaz, A. Pulido-Rojano, and G. Cañón-Zabala, "ISO 50001: 2018 and Its Application in a Comprehensive Management System with an Energy-Performance Focus," *Energies*, vol. 12, no. 24, p. 4700, 2019, doi: 10.3390/en12244700.

[280] E. Cagno, D. Accordini, A. Trianni, M. Katic, N. Ferrari, and F. Gambaro, "Understanding the impacts of energy efficiency measures on a Company's operational performance: A new framework," *Appl. Energy*, vol. 328, p. 120118, Dec. 2022, doi: 10.1016/j.apenergy.2022.120118.

[281] A. S. M. M. Hasan, M. Raza, M. Katic, and A. Trianni, "Towards a Framework Linking Industrial Energy Efficiency Measures with Production Resources," in *2021 11th International Conference on Power and Energy Systems (ICPES)*, Dec. 2021, pp. 856–860, doi: 10.1109/ICPES53652.2021.9683855.

[282] E. O. B. Nara *et al.*, "Expected impact of industry 4.0 technologies on sustainable development: A study in the context of Brazil's plastic industry," *Sustain. Prod. Consum.*, vol. 25, pp. 102–122, Jan. 2021, doi: 10.1016/j.spc.2020.07.018.

[283] S. G. García and M. G. García, "Industry 4.0 implications in production and maintenance management: An overview," *Procedia Manuf.*, vol. 41, pp. 415–422, Jan. 2019, doi:

10.1016/j.promfg.2019.09.027.

[284] F. Matsunaga, V. Zytkowski, P. Valle, and F. Deschamps, “Optimization of Energy Efficiency in Smart Manufacturing Through the Application of Cyber-Physical Systems and Industry 4.0 Technologies,” *J. Energy Resour. Technol. Trans. ASME*, vol. 144, no. 10, Oct. 2022, doi: 10.1115/1.4053868/1136667.

[285] C. Kulatunga, K. Bhargava, D. Vimalajeewa, and S. Ivanov, “Cooperative in-network computation in energy harvesting device clouds,” *Sustain. Comput. Informatics Syst.*, vol. 16, pp. 106–116, Dec. 2017, doi: 10.1016/j.suscom.2017.10.006.

[286] S. Nienke, H. Frölian, V. Zeller, and G. Schuh, “Energy-management 4.0: Roadmap towards the self-optimising production of the future,” in *ACM International Conference Proceeding Series*, Mar. 2017, vol. Part F1282, pp. 6–10, doi: 10.1145/3070617.3070621.

[287] G. Peralta, M. Iglesias-Urkia, M. Barcelo, R. Gomez, A. Moran, and J. Bilbao, “Fog computing based efficient IoT scheme for the Industry 4.0,” Jun. 2017, doi: 10.1109/ECMSM.2017.7945879.

[288] G. L. Tortorella, R. Giglio, and D. H. Van Dun, “Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement,” *Int. J. Oper. & Prod. Manag.*, vol. 39, no. 6/7/8, pp. 860–886, 2019, doi: 10.1108/ijopm-01-2019-0005.

[289] F. Tonelli, M. Demartini, A. Loleo, and C. Testa, “A Novel Methodology for Manufacturing Firms Value Modeling and Mapping to Improve Operational Performance in the Industry 4.0 Era,” *Procedia CIRP*, vol. 57, pp. 122–127, Jan. 2016, doi: 10.1016/J.PROCIR.2016.11.022.

[290] S. Ford and M. Despeisse, “Additive manufacturing and sustainability: an exploratory study of the advantages and challenges,” *J. Clean. Prod.*, vol. 137, pp. 1573–1587, Nov. 2016, doi: 10.1016/J.JCLEPRO.2016.04.150.

[291] C. J. H. Bauerdick, M. Helfert, B. Menz, and E. Abele, “A Common Software Framework for Energy Data Based Monitoring and Controlling for Machine Power Peak Reduction and Workpiece Quality Improvements,” in *Procedia CIRP*, Jan. 2017, vol. 61, pp. 359–364, doi: 10.1016/j.procir.2016.11.226.

[292] H. Junker and C. Domann, “Towards industry 4.0 in corporate energy management,” *WIT Trans. Ecol. Environ.*, vol. 214, pp. 49–56, Aug. 2017, doi: 10.2495/ECO170051.

[293] T. Wagner, C. Herrmann, and S. Thiede, “Industry 4.0 Impacts on Lean Production Systems,” *Procedia CIRP*, vol. 63, pp. 125–131, Jan. 2017, doi: 10.1016/J.PROCIR.2017.02.041.

[294] G. Beier, S. Niehoff, and B. Xue, “More Sustainability in Industry through Industrial Internet of Things?,” *Appl. Sci. 2018, Vol. 8, Page 219*, vol. 8, no. 2, p. 219, Jan. 2018, doi: 10.3390/APP8020219.

[295] S. Kamble, A. Gunasekaran, and N. C. Dhone, “Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies,” *Int. J. Prod. Res.*, vol. 58, no. 5, pp. 1319–1337, 2020, doi: 10.1080/00207543.2019.1630772.

[296] C. Favi, M. Marconi, M. Mandolini, and M. Germani, “Sustainable life cycle and energy management of discrete manufacturing plants in the industry 4.0 framework,” *Appl. Energy*, vol. 312, p. 118671, Apr. 2022, doi: 10.1016/J.APENERGY.2022.118671.

[297] L. M. Tumbajoy, M. Muñoz-Añasco, and S. Thiede, “Enabling Industry 4.0 impact assessment with manufacturing system simulation: an OEE based methodology,” *Procedia CIRP*, vol. 107, pp. 681–686, Jan. 2022, doi: 10.1016/J.PROCIR.2022.05.045.

[298] M. Vogt, C. Buchholz, S. Thiede, and C. Herrmann, “Energy efficiency of Heating, Ventilation and Air Conditioning systems in production environments through model-predictive control schemes: The case of battery production,” *J. Clean. Prod.*, vol. 350, p. 131354, 2022, doi: 10.1016/j.jclepro.2022.131354.

[299] G. Arana-Landín, N. Uriarte-Gallastegi, B. Landeta-Manzano, and I. Laskurain-Iturbe, “The Contribution of Lean Management—Industry 4.0 Technologies to Improving Energy Efficiency,” *Energies 2023, Vol. 16, Page 2124*, vol. 16, no. 5, p. 2124, Feb. 2023, doi: 10.3390/EN16052124.

[300] “IAC: IAC Technical Documents.” https://iac.university/technicalDocuments (accessed Jul. 13, 2021).

[301] M. R. Muller, K. Baber, and S. Landis, “Industrial Assessment Center Assessment Recommendation Codes (ARC),” *IAC Assessment Recommendation Code System*, vol. 19, no. 1. U.S. Department of Energy, 2019.

[302] J. Barney, “Firm Resources and Sustained Competitive Advantage,” *J. Manage.*, vol. 17, no. 1, pp. 99–120, Mar. 1991, doi: 10.1177/014920639101700108.

[303] A. D. Kretschmer, “Can Ideas Be Capital? Factors of Production in the Postindustrial Economy: A Review and Critique on JSTOR,” *Acad. Manag. Rev.*, vol. 32, no. 2, pp. 573–594, 2007, Accessed: Jul. 13, 2021. [Online]. Available: https://www.jstor.org/stable/20159316.

[304] H. Kaynak, “The relationship between total quality management practices and their effects on firm performance,” *J. Oper. Manag.*, vol. 21, no. 4, pp. 405–435, Jul. 2003, doi: 10.1016/S0272-6963(03)00004-4.

[305] S. Ismail Salaheldin, “Critical success factors for TQM implementation and their impact on performance of SMEs,” *Int. J. Product. Perform. Manag.*, vol. 58, no. 3, pp. 215–237, Mar. 2009, doi: 10.1108/17410400910938832.

[306] E. Bayraktar, M. Demirbag, S. C. L. Koh, E. Tatoglu, and H. Zaim, “A causal analysis of the impact of information systems and supply chain management practices on operational performance: Evidence from manufacturing SMEs in Turkey,” *Int. J. Prod. Econ.*, vol. 122, no. 1, pp. 133–149, Nov. 2009, doi: 10.1016/J.IJPE.2009.05.011.

[307] C. Corbett and L. Van Wassenhove, “Trade-offs? What Trade-offs? Competence and Competitiveness in Manufacturing Strategy:,” *http://dx.doi.org/10.2307/41166757*, vol. 35, no. 4, pp. 107–122, Jul. 1993, doi: 10.2307/41166757.

[308] D. Samson and M. Terziovski, “The relationship between total quality management practices and operational performance,” *J. Oper. Manag.*, vol. 17, no. 4, pp. 393–409, Jun. 1999, doi: 10.1016/S0272-6963(98)00046-1.

[309] C. J. C. Jabbour, A. B. L. De Sousa Jabbour, K. Govindan, A. A. Teixeira, and W. R. De Souza Freitas, “Environmental management and operational performance in automotive companies in Brazil: the role of human resource management and lean manufacturing,” *J. Clean. Prod.*, vol. 47, pp. 129–140, May 2013, doi: 10.1016/J.JCLEPRO.2012.07.010.

[310] N. Slack, “The changing nature of operations flexibility,” *Int. J. Oper. Prod. Manag.*, vol. 25, no. 12, pp. 1201–1210, 2005, doi: 10.1108/01443570510633602/FULL/HTML.

[311] F. R. J. R. Chase, *Operations and Supply Chain Management*, 16th ed. New York, USA: McGraw-Hill Education, 2020.

[312] C. J. Bamber, P. Castka, J. M. Sharp, and Y. Motara, “Cross-functional team working for overall equipment effectiveness (OEE),” *J. Qual. Maint. Eng.*, vol. 9, no. 3, pp. 223–238, Sep. 2003, doi: 10.1108/13552510310493684.

[313] A. J. De Ron and J. E. Rooda, “Equipment effectiveness: OEE revisited,” *IEEE Trans. Semicond. Manuf.*, vol. 18, no. 1, pp. 190–196, Feb. 2005, doi: 10.1109/TSM.2004.836657.

[314] M. Braglia, D. Castellano, M. Frosolini, M. Gallo, and L. Marrazzini, “Revised overall labour effectiveness,” *Int. J. Product. Perform. Manag.*, vol. 70, no. 6, pp. 1317–1335, Jun. 2021, doi: 10.1108/IJPPM-08-2019-0368.

[315] G. Nota, F. D. Nota, D. Peluso, and A. T. Lazo, “Energy Efficiency in Industry 4.0: The Case of Batch Production Processes,” *Sustain. 2020, Vol. 12, Page 6631*, vol. 12, no. 16, p. 6631, Aug. 2020, doi: 10.3390/SU12166631.

[316] S. Nakajima, *Introduction to TPM: Total Productive Maintenance*. New York, USA: Productivity Press Inc., 1988.

[317] G. San, T.-C. Huang, and L.-H. Huang, “Does labour quality matter on productivity growth? The case of the Taiwanese manufacturing industry,” *Total Qual. Manag. & Bus. Excell.*, vol. 19, no. 10, pp. 1043–1053, 2008, doi: 10.1080/14783360802264152.

[318] “Glossary – OEE Definitions and Manufacturing Improvement | OEE.” https://www.oee.com/oee-glossary.html (accessed Sep. 27, 2021).

[319] S. N. Chapman, *The Fundamentals of Production Planning and Control*. New Jersey, USA: Pearson Education Inc., 2006.

[320] E. S. Bernardes and M. D. Hanna, “A theoretical review of flexibility, agility and responsiveness in the operations management literature: Toward a conceptual definition of customer responsiveness,” *Int. J. Oper. Prod. Manag.*, vol. 29, no. 1, pp. 30–53, Jan. 2009, doi: 10.1108/01443570910925352/FULL/HTML.

[321] A. Dolgui, G. Levin, B. Rozin, and I. Kasabutski, “Cost optimization for series–parallel execution of a collection of intersecting operation sets,”

*http://dx.doi.org/10.1080/0305215X.2015.1056790*, vol. 48, no. 5, pp. 756–771, May 2015, doi: 10.1080/0305215X.2015.1056790.

[322] R. Saidur, "A review on electrical motors energy use and energy savings," *Renew. Sustain. Energy Rev.*, vol. 14, no. 3, pp. 877–898, Apr. 2010, doi: 10.1016/j.rser.2009.10.018.

[323] A. Trianni, E. Cagno, and D. Accordini, "Energy efficiency measures in electric motors systems: A novel classification highlighting specific implications in their adoption," *Appl. Energy*, vol. 252, p. 113481, Oct. 2019, doi: 10.1016/J.APENERGY.2019.113481.

[324] M. Hasanuzzaman, N. A. Rahim, R. Saidur, and S. N. Kazi, "Energy savings and emissions reductions for rewinding and replacement of industrial motor," *Energy*, vol. 36, no. 1, pp. 233–240, Jan. 2011, doi: 10.1016/J.ENERGY.2010.10.046.

[325] R. Saidur, N. A. Rahim, and M. Hasanuzzaman, "A review on compressed-air energy use and energy savings," *Renew. Sustain. Energy Rev.*, vol. 14, no. 4, pp. 1135–1153, May 2010, doi: 10.1016/J.RSER.2009.11.013.

[326] A. McKane and A. Hasanbeigi, "Motor systems energy efficiency supply curves: A methodology for assessing the energy efficiency potential of industrial motor systems," *Energy Policy*, vol. 39, no. 10, pp. 6595–6607, Oct. 2011, doi: 10.1016/j.enpol.2011.08.004.

[327] F. Ascione, L. Bellia, A. Capozzoli, and F. Minichiello, "Energy saving strategies in air-conditioning for museums," *Appl. Therm. Eng.*, vol. 29, no. 4, pp. 676–686, Mar. 2009, doi: 10.1016/j.applthermaleng.2008.03.040.

[328] L. Hang and D.-H. Kim, "Enhanced Model-Based Predictive Control System Based on Fuzzy Logic for Maintaining Thermal Comfort in IoT Smart Space," *Appl. Sci. 2018, Vol. 8, Page 1031*, vol. 8, no. 7, p. 1031, Jun. 2018, doi: 10.3390/APP8071031.

[329] "Replace V-Belts with Notched or Synchronous Belt Drives," Washington, DC, USA. Accessed: Jul. 24, 2021. [Online]. Available: https://www.energy.gov/sites/prod/files/2014/04/f15/replace_vbelts_motor_systemts5.pdf.

[330] "IAC: Search IAC Recommendations." https://iac.university/searchRecommendations?arcCode=2.41 (accessed Jul. 24, 2021).

[331] "Energy Savings with Motors and Drivers." Harwell, Ridcot, Oxfordshire, United Kingdom, p. 53, 1998.

[332] "United States Industrial Electric Motor Systems Market Opportunities Assessment." U.S. Department of Energy, Washington, DC, USA, p. 386, 2002.

[333] E. Worrell, "Managing Your Energy: An ENERGY STAR(R) Guide for Identifying Energy Savings in Manufacturing Plants." Jul. 29, 2010.

[334] "Energy surveys- a practical guide to identifying energy saving opportunities." Carbon Trust, London, United Kingdom, p. 53, 2011.

[335] "Optimizing Your Motor-Driven System." U.S. Department of Energy, Washington, DC, USA, p. 8, 1996.

[336] "Improving Motor and Drive System Performancece: A Sourcebook for Industry," Washington, DC, USA, 2014.

[337] D. Kaya, P. Phelan, D. Chau, and H. I. Sarac, "Energy conservation in compressed-air systems," *Int. J. Energy Res.*, vol. 26, no. 9, pp. 837–849, Jul. 2002, doi: 10.1002/ER.823.

[338] T. La, "Don't Let Compressed Air Blow Away Your Profits," *Energy Eng. J. Assoc. Energy Eng.*, vol. 111, no. 1, pp. 7–15, Dec. 2013, doi: 10.1080/01998595.2013.10769725.

[339] "Heat Recovery and Compressed Air Systems | Compressed Air Best Practices." https://www.airbestpractices.com/technology/air-compressors/heat-recovery-and-compressed-air-systems (accessed Jul. 28, 2021).

[340] "Energy Tips-Compressed Air Suggested Actions." U.S.A. Department of Energy, Washington, DC, USA, p. 2, 2004, Accessed: Jul. 28, 2021. [Online]. Available: www.eere.energy.gov/industry/bestpractices.

[341] R. Scot Foss, "Optimizing the compressed air system," *Energy Eng.*, vol. 102, no. 1, pp. 49–60, 2005, doi: 10.1080/01998590509509419.

[342] "Improving Compressed Air System Performance: A Sourcebook for Industry." U.S. Department of Energy, Washington, DC, USA, pp. 1–128, 2003.

[343] "Compressed air systems: Sealing up a productive manufacturing future for NSW." Australian Alliance for Energy Productivity, Sydney, Australia, p. 20, 2021.

[344] T. Markis and J. A. Paravantis, "Energy conservation in small enterprises," *Energy Build.*, vol. 39, no. 4, pp. 404–415, Apr. 2007, doi: 10.1016/J.ENBUILD.2006.08.006.

[345] E. H. Mathews, C. P. Botha, D. C. Arndt, and A. Malan, "HVAC control strategies to enhance comfort and minimise energy usage," *Energy Build.*, vol. 33, no. 8, pp. 853–863, Oct. 2001, doi: 10.1016/S0378-7788(01)00075-5.

[346] C. A. Balaras, E. Dascalaki, A. Gaglia, and K. Droutsa, "Energy conservation potential, HVAC installations and operational issues in Hellenic airports," *Energy Build.*, vol. 35, no. 11, pp. 1105–1120, Dec. 2003, doi: 10.1016/j.enbuild.2003.09.006.

[347] A. G. Gaglia, C. A. Balaras, S. Mirasgedis, E. Georgopoulou, Y. Sarafidis, and D. P. Lalas, "Empirical assessment of the Hellenic non-residential building stock, energy consumption, emissions and potential energy savings," *Energy Convers. Manag.*, vol. 48, no. 4, pp. 1160–1175, Apr. 2007, doi: 10.1016/J.ENCONMAN.2006.10.008.

[348] S. Kowsari and M. Deymi-Dashtebayaz, "Energy, exergy and exergoeconomic (3E) analysis and multi-objective optimization of a closed-circuit desalination system with side-conduit," *Desalination*, vol. 514, p. 115154, Oct. 2021, doi: 10.1016/J.DESAL.2021.115154.

[349] M. Gandiglio, A. Lanzini, A. Soto, P. Leone, and M. Santarelli, "Enhancing the Energy Efficiency of Wastewater Treatment Plants through Co-digestion and Fuel Cell Systems," *Front. Environ. Sci.*, vol. 0, p. 70, Oct. 2017, doi: 10.3389/FENVS.2017.00070.

[350] "Energy Efficiency Strategies for Municipal Wastewater Treatment Facilities." U.S. Department

of Energy, Colorado, U.S.A., pp. 1–25, 2012, [Online]. Available: https://www.nrel.gov/docs/fy12osti/53341.pdf.

[351] "Energy Efficiency Opportunities in Wastewater Treatment Facilities." Office of Environment & Heritage, NSW, Australia, Sydney, Australia, pp. 1–77, 2019, [Online]. Available: https://www.environment.nsw.gov.au/resources/business/wastewater-treatment-facilities-energy-efficiency-opportunities-190114.pdf.

[352] J. Krampe, "Energy benchmarking of South Australian WWTPs," *Water Sci. Technol.*, vol. 67, no. 9, pp. 2059–2066, May 2013, doi: 10.2166/wst.2013.090.

[353] S. Longo *et al.*, "Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement," *Appl. Energy*, vol. 179, pp. 1251–1268, Oct. 2016, doi: 10.1016/J.APENERGY.2016.07.043.

[354] H. S. Kang *et al.*, "Smart manufacturing: Past research, present findings, and future directions," *Int. J. Precis. Eng. Manuf. - Green Technol.*, vol. 3, no. 1, pp. 111–128, Jan. 2016, doi: 10.1007/s40684-016-0015-5.

[355] Y. Liao, F. Deschamps, E. de F. R. Loures, and L. F. P. Ramos, "Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal," *Int. J. Prod. Res.*, vol. 55, no. 12, pp. 3609–3629, Jun. 2017, doi: 10.1080/00207543.2017.1308576.

[356] L. Yu, B. Nazir, and Y. Wang, "Intelligent power monitoring of building equipment based on Internet of Things technology," *Comput. Commun.*, vol. 157, pp. 76–84, May 2020, doi: 10.1016/j.comcom.2020.04.016.

[357] A. S. M. M. Hasan and A. Trianni, "Towards a Framework to Assess the Impact of Industry 4.0 Technologies & Services on Production Resources," 2022, doi: 10.1109/ieem55944.2022.9989725.

[358] P. E. D. Love and J. Matthews, "The 'how' of benefits management for digital technology: From engineering to asset management," *Autom. Constr.*, vol. 107, p. 102930, Nov. 2019, doi: 10.1016/j.autcon.2019.102930.

[359] S. Y. Teng, M. Touš, W. D. Leong, B. S. How, H. L. Lam, and V. Máša, "Recent advances on industrial data-driven energy savings: Digital twins and infrastructures," *Renew. Sustain. Energy Rev.*, vol. 135, p. 110208, Jan. 2021, doi: 10.1016/J.RSER.2020.110208.

[360] M. Kerin and D. T. Pham, "A review of emerging industry 4.0 technologies in remanufacturing," *Journal of Cleaner Production*, vol. 237. Elsevier Ltd, p. 117805, Nov. 10, 2019, doi: 10.1016/j.jclepro.2019.117805.

[361] D. Newell, R. Twohig, and M. Duffy, "Effect of energy management circuitry on optimum energy harvesting source configuration for small form-factor autonomous sensing applications," *J. Ind. Inf. Integr.*, vol. 11, pp. 1–10, Sep. 2018, doi: 10.1016/j.jii.2017.04.002.

[362] Y. L. Chou, J. M. Yang, and C. H. Wu, "An energy-aware scheduling algorithm under maximum power consumption constraints," *J. Manuf. Syst.*, vol. 57, pp. 182–197, Oct. 2020, doi:

10.1016/J.JMSY.2020.09.004.

[363] Z. He, H. Xi, T. Ding, J. Wang, and Z. Li, “Energy efficiency optimization of an integrated heat pipe cooling system in data center based on genetic algorithm,” *Appl. Therm. Eng.*, vol. 182, p. 115800, Jan. 2021, doi: 10.1016/J.APPLTHERMALENG.2020.115800.

[364] J. Wan, B. Chen, S. Wang, M. Xia, D. Li, and C. Liu, “Fog Computing for Energy-Aware Load Balancing and Scheduling in Smart Factory,” *IEEE Trans. Ind. Informatics*, vol. 14, no. 10, pp. 4548–4556, Oct. 2018, doi: 10.1109/TII.2018.2818932.

[365] T. Ahmad *et al.*, “Energetics Systems and artificial intelligence: Applications of industry 4.0,” *Energy Reports*, vol. 8, pp. 334–361, Nov. 2022, doi: 10.1016/J.EGYR.2021.11.256.

[366] A. Hasanbeigi and L. Price, “A review of energy use and energy efficiency technologies for the textile industry,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 3648–3665, Aug. 2012, doi: 10.1016/j.rser.2012.03.029.

[367] A. Soualhi, G. Clerc, and H. Razik, “Detection and diagnosis of faults in induction motor using an improved artificial ant clustering technique,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 9, pp. 4053–4062, 2013, doi: 10.1109/TIE.2012.2230598.

[368] W. Lee, H. Jeoung, D. Park, T. Kim, H. Lee, and N. Kim, “A Real-Time Intelligent Energy Management Strategy for Hybrid Electric Vehicles Using Reinforcement Learning,” *IEEE Access*, vol. 9, pp. 72759–72768, 2021, doi: 10.1109/ACCESS.2021.3079903.

[369] Wenping Cao and K. J. Bradley, “Assessing the impacts of rewind and repeated rewinds on induction motors: is an opportunity for Re-designing the machine being wasted?,” *IEEE Trans. Ind. Appl.*, vol. 42, no. 4, pp. 958–964, Jul. 2006, doi: 10.1109/TIA.2006.876069.

[370] J. R. Gómez *et al.*, “Assessment criteria of the feasibility of replacement standard efficiency electric motors with high-efficiency motors,” *Energy*, vol. 239, p. 121877, Jan. 2022, doi: 10.1016/j.energy.2021.121877.

[371] “Effects of Dust and Debris on Operations in Your Site.” https://www.hunterindustrialsupplies.com.au/blog/effects-of-dust-and-debris-in-your-site/ (accessed Oct. 20, 2021).

[372] “The Secret Damage Of Dust - Transcendent: EAM | CMMS | Logistics.” https://transcendent.ai/blog/asset-management/the-secret-damage-of-dust/ (accessed Oct. 20, 2021).

[373] S. Sauvé, S. Lamontagne, J. Dupras, and W. Stahel, “Circular economy of water: Tackling quantity, quality and footprint of water,” *Environ. Dev.*, vol. 39, p. 100651, Sep. 2021, doi: 10.1016/J.ENVDEV.2021.100651.

[374] B. Marchi, S. Zanoni, and M. Y. Jaber, “Economic production quantity model with learning in production, quality, reliability and energy efficiency,” *Comput. Ind. Eng.*, vol. 129, pp. 502–511, Mar. 2019, doi: 10.1016/j.cie.2019.02.009.

[375] D. C. Fettermann, C. G. S. Cavalcante, T. D. De Almeida, and G. L. Tortorella, “How does

Industry 4.0 contribute to operations management?," *J. Ind. Prod. Eng.*, vol. 35, no. 4, pp. 255–268, 2018, doi: 10.1080/21681015.2018.1462863.

[376] Y. S. Tan, Y. T. Ng, and J. S. C. Low, "Internet-of-Things Enabled Real-time Monitoring of Energy Efficiency on Manufacturing Shop Floors," in *Procedia CIRP*, Jan. 2017, vol. 61, pp. 376–381, doi: 10.1016/j.procir.2016.11.242.

[377] I. Laskurain-Iturbe, G. Arana-Landín, B. Landeta-Manzano, and N. Uriarte-Gallastegi, "Exploring the influence of industry 4.0 technologies on the circular economy," *J. Clean. Prod.*, vol. 321, p. 128944, Oct. 2021, doi: 10.1016/J.JCLEPRO.2021.128944.

[378] A. B. Lopes de Sousa Jabbour, C. J. C. Jabbour, M. Godinho Filho, and D. Roubaud, "Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations," *Ann. Oper. Res.*, vol. 270, no. 1–2, pp. 273–286, Nov. 2018, doi: 10.1007/s10479-018-2772-8.

## Appendix A

Topic: Validation of Framework for Energy Efficiency Measures
Name of the interviewee:
Occupation/designation and work place:
Date: ____/____/________ (dd/mm/yyyy)
Interview structure: Semi-Structured
Time: Around 1 hour

Question 1. What specific sector does your company primarily focus on within the energy industry? Please provide details regarding the industry, such as renewable energy, oil and gas, manufacturing, or any other relevant sector?

Question 2. Could you please elaborate on your role and responsibilities in the company? This could include your position within the company, your area of expertise, and the scope of your involvement in energy-related projects.

Question 3. How many years of experience do you have working in the energy sector? It would be helpful to know the duration and depth of your experience to better understand your perspective.

Question 4. In terms of the framework's category and attributes, do you find it inclusive and comprehensive? Specifically, does it cover a wide range of energy efficiency measures and account for various aspects of energy management?

Question 5. From your expert viewpoint, how usable and practical is the framework? Have you found it effective in guiding organizations through the process of identifying, selecting, and implementing EEMs? Please provide examples or insights from your experience.

Question 6. Considering real-world scenarios, do you find the framework convenient to use? Does it offer clear guidelines and practical steps that can be easily followed by organizations seeking to improve their energy efficiency?

Question 7. Have you observed any challenges or areas where the framework could be further enhanced to enhance its convenience?

## Appendix B

Topic: Role of I4.0 technologies to boost the performance of EEMs

Name of the interviewee:

Occupation/designation and workplace:

Date: ____/____/________ (dd/mm/yyyy)

Interview structure: Semi-Structured

Time: Around 2 hour

1. Manufacturing: What types of products or goods does the company manufacture?
2. Does this company have any certification (e.g. ISO 9001, ISO 50001)?
3. Energy Usage:
    a. What is the overall energy consumption of the company in its manufacturing operations?
    b. What are the specific areas or processes within the company that account for a significant portion of the energy usage?
    c. Have there been any efforts to monitor and optimize energy consumption in different stages of the manufacturing process?
4. Annual Turnover: What is the company's annual turnover?
5. Main Functions: What are the key functions or activities carried out by the company in its industry?
6. Energy Efficiency Measures:
    a. What specific energy efficiency measures have been implemented by the company?
    b. How were these measures identified and selected?
    c. What factors were considered in the implementation of EEMs?
7. Impact on Production Resources:
    a. Have the energy efficiency measures had any observable impact on the company's production resources (e.g., machinery, equipment, materials)?
    b. Are there any notable improvements in resource utilization, optimization, or longevity as a result of the energy efficiency measures?
8. Operational Performance Improvement:
    a. Have the energy efficiency measures resulted in any improvements in the company's operational performance?
    b. Are there any specific performance indicators or metrics used to track and evaluate the impact of energy efficiency on operational performance?
9. Industry 4.0 Technologies:
    a. What specific Industry 4.0 technologies have been implemented by the company in relation to energy efficiency and manufacturing performance?

b. How were these technologies selected?
c. Have you implemented any specific Industry 4.0 technologies in your manufacturing processes that have resulted in observed improvements in energy savings?
d. Has the implementation of I4.0 technologies improved the performance of the energy efficiency measures?
e. Have the Industry 4.0 technologies had any impact on the company's production resources?
f. How have these technologies influenced the overall performance in the manufacturing process?
g. Have you also encountered any instances where negative impacts or challenges have emerged?
h. Are there any specific Industry 4.0 technologies that you are considering for implementation in the near future?