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Decentralised energy futures: the changing emissions reduction landscape

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Abstract

The world is witnessing an energy revolution as renewables become more competitive and energy security becomes a high priority for an increasing number of countries. This development is changing the point along the supply chain ripe for reducing emissions. Whereas carbon capture and storage (CCS) coupled to coal or gas power production offers the potential to decarbonise the current centralised power systems, this relies on a significant increase in electrification to achieve deep emission reductions beyond the power sector, including industrial emissions and transportation. At the same time there is a trend towards decentralised industrial processes, e.g., driven by cost reductions in decentralised production systems and miniature processing plant. New strategies for reducing emissions from decentralised industrial and energy emission point sources will be increasingly important. This paper evaluates different emission reduction strategies that may be relevant to a decentralised energy and manufacturing future, including increased electrification, energy storage, renewable energy and renewable feedstock. Systemic opportunities or barriers and considerations of policy and decentralised decision-making are examined.

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1. Introduction

Energy technology developments as well as energy and climate policies are leading to a global shift towards low-carbon electricity generation. Currently electricity generation contributes about 83 % of global greenhouse gas emissions owing to the major reliance on coal-fired power [2]; a shift to a low-carbon electricity system involves the deployment of a more varied combination and scale of electricity generators, including: renewables, combined cycle gas turbines (CCGTs), and conventional fossil fuel plants with carbon capture and storage (CCS).

There has been major recent development of renewable generation capacity from small scale, e.g. rooftop solar at the kW scales, to larger scales of the order of 100s of MWs. It is important to note that what may be defined as ‘large-scale’ renewables (say > 10 MW) is relatively small compared to a typical coal-fired power plant, greater than 500 MW. Moreover, the definition of “decentralized” is often pointed out as unclear, although some useful definitions are provided elsewhere [3, 4]. Economies of scale have driven investment in these conventional fossil fuel power plants that currently underpin the established centralised energy systems. Whilst increasingly larger renewable energy systems are being built in Europe, USA and China, the significant integration of diverse renewable generators across a range of scales reflects a shift towards a more distributed energy system model, as shown in Figure 1. There are advantages, in terms of energy security as well as emission reductions if renewables offset fossil generation [5]. This paper considers the implications of such technology trends for the emission reduction landscape.

A significant investment in new energy infrastructure is necessary to achieve major emission reduction across all sectors, while maintaining an affordable and reliable electricity supply and industrial output. A key strategy to achieve emission reductions beyond the power sector is an increase in electrification using low-carbon electricity supply to displace fossil fuel use in industry, buildings and the transport sectors. An alternative strategy involves a transition to a hydrogen energy economy underpinned by the production of low-carbon hydrogen used in hydrogen fuel cells. Both approaches require a significant increase in low-emission power generation capacity and infrastructure for storage and distribution. Moreover, they require specific considerations of industry characteristics which may prevent or enable uptake [6].

From the viewpoint of the demand side, the manufacturing industry is required to use low-carbon energy sources and reduce energy consumption. At the same time, the manufacturing industry has been undergoing decentralisation – for example by using 3D printing technologies. Towards designing sustainable manufacturing industries, there is a need to consider the transformation of both energy supply systems and industrial production systems in conjunction. In this paper, different emission reduction strategies are evaluated by taking into account decentralised energy and manufacturing futures, such as increased electrification, energy storage and renewable energy.

The importance of considering both decarbonisation and decentralisation is a key element of this paper – as the two

trends do not necessarily lead to optimal future scenarios either economically or environmentally.

2. Key technologies available for decarbonisation

This section describes in brief a number of key technologies for transition to decentralized energy systems. While many renewable energy technologies are available, the current front-runners for decentralized systems are wind and solar – other technologies such as geothermal, micro-hydro and biomass are not addressed.

2.1. Wind

The development of wind turbine technology in the last 30 years probably represents the most successful of all new

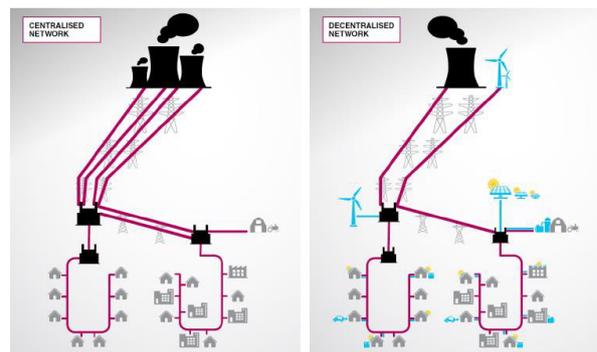


Figure 1: Changes from centralised to decentralised energy systems (Image used with permission from [1])

generation technology with deployment of more than 270 GW globally in 2012 [7]. Standard commercial units today are ‘Danish design’ units with capacities of up to 3 MWs (largest units up to 8MW) and capacity factors in the range 30-40 % at good sites, with excellent turbine reliability. Because they rely on a variable wind resource, significant increments of wind power within an electricity network can pose operational challenges; however, wind penetrations of 20-30% are being successfully managed in some jurisdictions, e.g., Denmark [7].

2.2. Solar

Large-scale solar includes three main technologies, solar photovoltaic (PV), concentrated solar thermal (CST) and concentrated PV (CPV). All of these technologies are technically viable and have been demonstrated at large-scales (at least 1 MW) around the world. PV technology converts sunlight directly into electricity. CST uses reflectors or lenses to focus sunlight from a large area onto a small receiver that absorbs the solar radiation and heats up a fluid (water or oil) used to produce steam for a steam power-cycle. CST technology can also be integrated with fossil fuel (or biomass) power systems to boost output, or to displace some fossil-fuel input. CPV is a hybrid technology with the PV cells built into collectors that use reflectors and lenses to concentrate the light onto the PV cell.

Solar PV, mostly small-scale rooftop installations, reached 100 GW worldwide (4 % is >10 MW), making PV number

three in terms of installed renewable capacity after wind and hydro and stimulated by a reduction in costs as well as incentives, e.g., feed-in-tariffs [7]. 99 % of this capacity is grid-connected. The number and scale of large-scale solar PV is increasing with 400 plants > 10 MW in early 2013. Most of these large facilities are in Europe, USA, and China including the largest PV facility that is 250 MW in Arizona [7]. CSP reached a capacity of 2550 MW in 2012 with a significant proportion of the capacity installed in Spain (1,950 MW).

2.3. CCGT

Fuel switching from coal to gas for power generation has the potential to halve emissions relative to a conventional coal fired power plant. Over the past decade, gas generation has contributed more to new global capacity than any other technology, with the exception of coal generation additions in China and India, contributing about 20% of global power output. The main drivers for this development have been a growing gas market availability, lower relative capital costs and environmental impacts, and greater operating flexibility relative to coal or nuclear. Combined cycle gas turbine (CCGT) is the major gas generation technology incorporating an additional heat recovery boiler, fed by the waste heat from the gas turbine, and a steam turbine with thermal efficiencies approaching 60 % (LHV) [8].

2.4. CCS

CCS technology can deliver low-emission electricity by preventing the CO₂ being released into the atmosphere that is produced during the combustion (post-combustion capture) or gasification (pre-combustion capture) of the fossil fuels. CCS can be applied to coal and gas plants and it offers two unique decarbonisation options relative to the other low-emission technologies: (i) CCS can be retrofitted to existing power plants, and (ii) can offset industrial emissions, e.g., from gas processing, cement, and iron and steel that is not possible with renewable energy technology.

Near-pure captured CO₂ can then be pressurised for transport in pipelines and used as a feedstock for industrial processes or injected into deep (1 km) geological formations for permanent storage. There is a significant energy cost associated with the capture and pressurization equivalent to about 25 % of the power output from a coal plant assuming commercially available amine-based solvent technology is used for capture.

Thus, CCS refers to a broad range of technologies for capture, transportation, and storage and all of the individual technologies have been employed at commercial scales for applications in the oil and gas and chemicals industries and a fully integrated CCS project in Norway has been in operation for separating CO₂ from raw natural gas for nearly two decades, with storage in a saline aquifer under the North Sea [9]. The first commercial application for power commenced operation in October 2014 in North America [10]. The CO₂ captured from this plant is used for enhanced oil recovery (EOR) providing a revenue stream to offset part of the costs of operating the capture plant. This is possible in North America where there

already exists an established market for CO₂ for EOR. Elsewhere, under current electricity and carbon policies, the commercialization of CCS power projects will likely require additional incentives to cover the operating expenses.

2.5. Hydrogen

Hydrogen as a potential low-carbon energy carrier has been discussed widely and in various national and industrial contexts (e.g. [11, 12]). Hydrogen can be considered as decentralized energy in its role as a storage material for renewable energy or in its role as a stored fuel used to generate electricity. Currently hydrogen is largely produced from fossil fuels – coal gasification and steam reforming of natural gas – for use in the petrochemical and ammonia industries. For decentralized hydrogen production, steam reforming or electrolysis are the most likely technologies. At the utilization end, fuel cells – often with combined heat and power systems – are the most widely promoted candidate technologies due to their high efficiency. Small-to-medium scale systems for hydrogen production and generation are readily available, although cost is a barrier to their widespread uptake.

3. Decentralisation of energy and industrial processing

The move towards renewable energy technologies almost inherently drives towards a decentralized energy system, but on the usage end centralized large-point-demand is also seeing potential changes. In modern industrial economies, the concept of “economies of scale” has led to large, often automated, industrial operations that can minimize the duplication of ancillary equipment and labor per unit of output. From an engineering perspective, larger equipment is often more efficient due to the ability to attain more extreme conditions and to maintain continuous throughput whilst reducing losses. It should be noted that in the renewables sector the same economies of scale are not present to the same extent – most of the renewable technologies are inherently modular, and therefore the efficiency of generation is less effected by size. The auxiliary equipment and storage of energy may be one exception.

Much of the centralization of industries has been based on the subsequent economic efficiencies obtained. Four supply-chain trends may run counter to this trend, and would have significant implications for the potential of decarbonisation of the economy. The four trends considered here are:

1. auto-electric generation;
2. onsite hydrogen generation;
3. bespoke manufacturing enabled by digital technologies such as 3D printing; and,
4. electrification and computerisation in industry.

The first of these trends is an extension of decentralized energy, whereby industrial operations seek to enhance energy supply security, reduce costs, utilize waste streams effectively and possibly offset costs by sales of excess energy. This trend has been widespread for a number of industries, including steel manufacturing, automotive manufacturers and alumina smelters, particularly in industries where large amounts of heat

are used [6], with the potential for cogeneration as CHP (Combined heat and power). Such operations tend to be on the smaller end of fossil fuel power plants, thus the potential for CCS could be considered limited without investment in shared infrastructure for transport, utilisation and/or storage. Conversely, the application of CHP can enable significant overall efficiency gains in the use of energy – with up to 75% or more of the available energy being utilised effectively. Added to this the reduction in transmission losses of (nominally) 5-10% may improve the effective carbon intensity significantly.

The second trend is still largely in its infancy, but with moves towards the utilisation of fuel cells in vehicles and homes, it is gradually becoming a reality. The roll-out of infrastructure for centralised production of hydrogen and piped distribution is often considered too expensive for an early-stage market, with decentralised hydrogen generation more attractive initially [13]. Steam reforming of natural gas is the most likely candidate for early, distributed generation of hydrogen as it provides good efficiency and scalability – it is also applied in the domestic fuel cell systems currently sold in Japan. Steam reforming leaves a relatively concentrated CO₂ stream and current practise is to emit this to the atmosphere. Additional process equipment would be required for CO₂ purification for further utilisation, thus again, decentralised operations are likely to be small scale – particularly in the initial phases, thus giving less attraction for CCS.

The third trend, utilising digital technologies to enable distributed (near to consumer) manufacturing, is exemplified by the opportunities of 3D printing. If the production of parts can be undertaken at distributed locations, implying smaller operations, then the quantities of any fuel will be dispersed and the ability to harness either CHP or CCS is largely lost. While this may not be an effective barrier for renewables in the case of low-intensity industries, energy intensive manufacturing processes will not likely be compatible.

A fourth trend, which is somewhat broader and effectively covers much of the ground of the previous section, is the ever-increasing rate of electrification and computerisation in industry. The trend in electrification has seen a doubling, from 9% of total final energy consumption (globally) in 1971 to 18% in 2011 [14]. General electrification is most prominent in (i) non-ferrous metals, (ii) machinery, and (iii) commercial and public services sectors, with the latter two sectors having shown the greatest increase over the period 1971-2011 [14].

While electricity may be supplied by a wide range of low-carbon technologies, the renewable energy sources are often hindered by intermittency, which can be overcome with sufficient storage and buffering, but at a higher cost than conventional technologies and often with a compromise in its “renewability” through the use of supplementary fuels. In particular, large commercial and industrial operations requiring uninterrupted power supplies of a high quality and power may not accept the potential variability of renewables – even with buffer capacity.

4. Opportunities and barriers

Each of the technology strategies for reducing carbon emissions from electricity has different opportunities and barriers. Some of these are related to scale (as mentioned above) while others will provide alternative challenges or

opportunities. Table 1 offers an initial examination of some of the factors that may be important in understanding the applicability of alternative strategies.

It is important to note that many of the emerging energy technologies – e.g. wind, solar photovoltaics, hydrogen fuel cells – are modular and scalable, making them inherently flexible installations. However, renewable energy technologies are locationally-restricted, requiring appropriate climatic conditions to function, which can constrain the availability of these technologies.

Moreover, the consideration of the need for back-up power capacity to supplement in the case of intermittent renewables makes both an argument for storage technologies such as hydrogen and batteries to avoid a reduction in efficacy as a low-carbon solution. In addition, low capacity ratios of storage technologies and back-up power for renewable energy systems due to intermittent outputs increase the electricity cost per kWh.

While infrastructure requirements are universal impediments to new energy technologies, in the case of small scale renewables located near to the grid and/or the end user, this is likely to be a minimal concern. On the other hand, the requirements for extensive Hydrogen or CO₂ pipelines – particularly in urban areas – may be a greater barrier to hydrogen or distributed CCS technologies. CCS itself is more applicable to large scale point sources, at which the cost (both in energy and monetary terms) of capture, compression and storage of CO₂ becomes more feasible to absorb. In the case of a widely connected grid, centralized CCS is likely to have advantages of cost and the ability to supply consistent, controllable energy.

Off-grid solutions for decentralized energy compete in a different market, whereby the investment in transmission lines is not cost effective to supply from a centralized grid. In such situations, renewable technologies with storage of electricity as hydrogen or in batteries is in competition with conventional diesel engines [15]. The advantage of having a local energy source, with no need to import fuel can be seen in case of natural disasters (although renewables may also be affected in some cases) [5]. In such a market, CCS cannot compete effectively, making the renewable solutions more attractive.

4.1. Decentralisation or decarbonisation?

Whilst there is an opportunity through renewable technologies to provide decarbonized, decentralized energy supplies, this is not always the case. As a case in point, motivations for decentralization are not universally consistent, and often the consideration of decarbonisation is not one of the main priorities. In the case of remote, isolated areas and commercial or industrial operations, the first priority is the security of energy supply (including cost of operation) which may run against the use of wind or solar power in certain locations – particularly when storage batteries must be included. Likewise, hydrogen storage is costly under current conditions and the use of other liquid or gaseous fuels is more convenient. On the other hand, renewables and hydrogen are earlier in the cost maturity curve, and are likely to see reductions in price, where fossil fuels are more likely to rise in price with time. Supplying fossil fuels to remote sites typically

incurs a price premium that may also work in favor of other low-carbon technologies.

Decarbonisation on the other hand, can be either centralized or decentralized. CCS is essentially a centralized technology, requiring a large, preferably highly concentrated, stream of CO₂ and a centralized sink. Considering coal as a benchmark, decentralisation through the use of CCGT may promote the reduction in emissions by up to 70%, whereas the utilization of CCS in a centralized configuration may eventually reduce 90% of emissions. On the other hand, the cost and social acceptance of CCS, and the efficiency losses associated with it, may make it less competitive.

5. Conclusions

A range of emission reduction technology options were evaluated in the context of a shift to a decentralised energy and manufacturing future. Such a shift may be characterised by an increase in the trend towards decentralisation to include industrial activities (possibly facilitated by new digital technologies), increased electrification, and greater utilisation of fuel cell technology. Systemic opportunities or barriers and considerations of policy and decentralised decision-making were examined. The applicability of mitigation technologies at scale is highlighted as a key point for consideration, e.g., the potential for CCS that may be important for dramatic emission reductions is considered limited without investment in shared infrastructure for transport, utilisation and/or storage and is certainly less likely in a decentralised energy scenario.

This paper has not covered the full extent of the implications of such technology shifts, but the field is open for further exploration. It is apparent that various competing priorities will inevitably affect the configuration of decentralised energy systems and their effectiveness in mitigating emissions. Importantly, it is argued that decentralisation and decarbonisation should not automatically be considered together – in many cases the systemic requirements of one would reduce the effectiveness of the other. Moreover, appropriate demand-supply matching is important, and a full supply chain consideration necessary for the most beneficial, sustainable energy system to be developed.

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Table 1: Decarbonisation technologies and considerations for decentralised operations

Decarbonisation technology	Technical maturity level	Scale of operation	Sectorial applicability	Opportunities and challenges in transition to decentralised operations
Wind	HIGH	~5kW – 10MW (unit) >1GW (windfarm)	power	Well suited to decentralised power, limited by variable wind resource requiring back-up and/or storage
Solar	HIGH	~1kW – 250MW	power	Very well suited to decentralised power, can be applied from kW-GW scales, limited by variable solar resource, however thermal storage available for CSP and good integration with existing fossil plant
CCGT (fuel switching)	HIGH	~100MW – 500MW	power and chemical and refineries	Good applicability to large scale decentralised power and industrial industries, CCS necessary for achieving very low emissions
CCS	HIGH –individual components LOW– fully integrated <i>commercial application for power limited</i>	>300MW	power, cement, iron and steel, refineries	Suitable for retrofit to existing coal and gas plant. Unique synergy with cement and can be applied for emission reductions for iron and steel. Applicable for large-scale decentralised industrial parks to exploit common infrastructure for storage. Less applicable to likely smaller scaled distributed processes.
Hydrogen	MEDIUM	~5kW – >350MW	Power CHP	Applicability at various scales; modular and appropriate for decentralised power – as both storage of renewable energy and generation of electricity. Onsite electrolysis linked to renewables is a likely later entry while current small-scale systems utilise gas steam reforming.