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Centralised and distributed electricity systems[☆]

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ABSTRACT

Because of their high level of integration, centralised energy supply systems are vulnerable to disturbances in the supply chain. In the case of electricity especially, this supply paradigm is losing some of its appeal. Apart from vulnerability, a number of further aggravating factors are reducing its attractiveness. They include the depletion of fossil fuels and their climate change impact, the insecurities affecting energy transportation infrastructure, and the desire of investors to minimise risks through the deployment of smaller-scale, modular generation and transmission systems.

Small-scale decentralised systems, where energy production and consumption are usually tightly coupled, are emerging as a viable alternative. They are less dependent upon centralised energy supply, and can sometimes use more than one energy source. They are less sensitive to the uncertain availability of remote primary energy and transportation networks. In addition, the close connection between energy generation and use makes decentralised systems cleaner because they are most often based on renewable energies or on high-efficiency fossil fuel-based technologies such as combined heat and power (CHP). Fully decentralised energy supply is not currently possible or even truly desirable. The secure and clean energy systems of the future will be those flexible enough to allow for a spectrum of hybrid modes of operation and investment, combining the best attributes of both paradigms. A large part of this flexibility will come from the networks that make it possible to combine these two types of infrastructures and obtain the benefits of both approaches.

1. Introduction and background

The classic energy supply chain can be summarised quite succinctly. First, primary energy is harvested remotely and may be transformed; it is then transported before it is finally utilised. This description allows us to identify the main strengths and weaknesses of such systems. Over the years, centralised systems have provided the potential for efficient resource allocation, and generated substantial economies of scale in the process of building and operating very reliable energy transportation and conversion plant. Nonetheless, because of their high level of integration, centralised systems can be vulnerable to disturbances within the supply chain. This is why the once-clear advantages of this energy supply paradigm have been rapidly fading, especially with the depletion and climate change impact of fossil primary energy, insecurities affecting the energy transportation infrastructure and the risky nature of large-scale plant investments.

Interest in decentralised energy supply systems has been growing constantly, especially in the case of electricity supply. The issues we have mentioned are driving the development of more decentralised systems, which are characterised by the proximity and coupling of electricity generation and utilisation sites. These electric energy systems are relatively independent of the main electricity supply chain and can use other sources of energy such as natural gas. This means that they are less sensitive than centralised systems to the uncertain availability of remote generation and of transmission networks. In the mainstream media, these systems are increasingly associated with the benefits from virtually free, low-carbon and locally available renewable energy resources such as wind and solar power. But in the specific context of the built environment, the emphasis is on decentralised electricity generation associated with heat production.

The reality is, however, that fully decentralised systems are not necessarily desirable. Decentralisation is instead part of a more global solution. The secure, clean and economically sound electric energy systems of the future will be those flexible enough to allow for a spectrum of hybrid modes of operation and investment, combining the best attributes of centralised and distributed systems. One way this flexibility will be achieved is through new approaches to network design and exploitation, which will allow the two types of infrastructure to work in symbiosis.

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The present review explores the current state of research on technology, business and policy with respect to the two energy supply infrastructure models. We also elaborate on how future scientific research and development effort will influence the evolution and the modes of interaction of the two supply paradigms to year 2050 and beyond. We will stress the fact that the current evidence points towards the deployment of an increasingly decentralised energy supply infrastructure, which will still rely on and benefit from common centralised infrastructures. The focus of the review will be mostly on electric energy systems and on energy systems combining heat and electricity. This is not to diminish the importance of gas, oil and coal supply infrastructure issues. But discussing the supply infrastructures for these resources is not as instructive as for heat and electricity, since for most practical purposes these sources of energy must be supplied in a centralised manner.

2. State of current science and technology

Since the onset of the 21st century, a number of events have brought to the fore the vulnerability of the current centralised energy supply infrastructure:

Terrorist threats: Acts of terrorism against primary energy production and transportation infrastructure are commonplace in many troubled areas of the globe. With the current level of integration of the supply chain, these events can end up affecting dramatically end-user prices and supply security.

Natural disasters: Increasingly extreme weather, possibly fuelled by the warmer climate, is also contributing to the loss of appeal of the current systems. In the aftermath of Hurricane Katrina in 2005, all oil and gas production, transport and refining in the southeast of the USA was paralysed.

Geopolitical disruptions: Unilateral decisions by primary energy exporting or transit countries can have dire consequences. The row over natural gas prices during the winter of 2005/06 led Russia to cut its supply to Ukraine.

Ageing of a highly complex infrastructure: A great portion of electricity supply and transportation equipment is approaching the end of its usable lifetime. This infrastructure is connected in intricate networks where the laws of physics ignore political boundaries, and over which intensified trading is taking place following electricity market liberalisation. In the August 2003 North American and the November 2006 pan-European blackouts, we witnessed how this complexity and vulnerability can cause widespread social and economic disruptions.

Climate change: Large central power stations using coal, oil and gas produce large amounts of the greenhouse gases which are altering the global climate. The general inefficiency of these plants makes matters worse as they produce significant amounts of waste heat, and require electricity to be transported to consumers over lossy transmission and distribution lines.

Regulatory and economic risks: In today's competitive and rapidly evolving industry, building new large central electricity generation and transmission plant proves to be increasingly difficult because of the ever more complex approval processes and the need to raise massive amounts of capital.

2.1. A flexible and resilient energy supply infrastructure

It is evident that shifting one's reliance from a few centrally provided energy sources to many more smaller-scale and local sources might improve reliability and security of supply through using more energy sources. It would improve energy efficiency and so lower the national carbon footprint through a reduction in transportation and energy conversion losses as well as through the ability to use waste heat (Lovins, 2005). It would also make plant investments less risky because decentralised generation technologies tend to be smaller and more modular. In the specific case of electricity, however, centrally operated bulk electric power transmission systems are still desirable and necessary. Even in the most optimistic scenarios, remote energy harvesting, for instance through extensive offshore wind farming in areas far from load centres, will be needed to meet the clean energy needs of growing economies (Ault et al., 2005). A more decentralised infrastructure would also benefit from networking through a number of technical and economic opportunities including assistance in times of low local energy availability and prospective sales of surplus energy. The high costs of some emerging technologies may also prohibit their deployment in a decentralised fashion. A good example is carbon capture and sequestration, which would generally make economical sense only when applied to a central plant infrastructure (Hoffert et al., 2002).

However, to achieve this vision, central networks have to evolve over the long run away from rigid unidirectional power flow and top-down supervisory control philosophies. Networks of the future are predicted to be interactive. They will permit bidirectional energy flow, where control is distributed and connection standards are closer to being 'plug-and-play', in a way inspired by the internet (European Commission, 2006).

The key to achieving this vision is by focusing research on making electricity supply systems more flexible. Flexibility is needed to provide some supply insurance in the light of uncertain primary energy and network availability, and to permit a range of hybrid operation modes and strategies, adaptable to prevailing wider network and local conditions. We detail below the research areas that have the potential to deliver this flexibility.

2.2. Decentralised energy harvesting and conversion

Research and development on harvesting distributed renewable energy focuses first on the improvement of energy capture and conversion efficiencies. Fuelled chiefly by innovation in material science and manufacturing, the goal here is to get ever closer to the theoretical limits imposed by the basic physics of these systems. The classic example concerns wind turbines, which have a theoretical maximum efficiency of 59%, the Betz limit, as compared to roughly 30% for commercial units (Hoffert et al., 2002).

The second important research effort concentrates on reducing manufacturing costs and addresses the up- and down-scaling of renewable generation plant. Direct consequences of these advances in manufacturing are the increasingly large wind turbines now available and the large decrease in per unit costs of photovoltaic cells.

Combined heat and power (CHP) technologies have been synonymous with decentralised electricity generation over the last few years. They are increasingly popular in industries with dual electric–thermal loads, including chemical processing as well as pulp and papermaking. Moreover, because of the widespread presence of district heating systems, CHP installations have recently been developing rapidly in the Scandinavian countries.

The main positive feature of CHP is the effective reduction of losses in the energy transportation system, because electricity is generated *in situ*, and in energy conversion, since waste heat in the electricity generation process is recovered for space and water heating, for cooling and for industrial process heat. (We note as well that the opposite, whereby electricity generation is coupled to a primary heat generation process, also applies.) In addition, CHP units can increase the security of supply in case the electrical grid is unavailable, and provide opportunities to sell surplus energy into the grid. The downside generally associated with CHP-produced electricity is its dependence on the central supply of a primary fuel, natural gas for the most part. This is a limiting factor in light of the uncertainties in the security of gas supplies. The viable alternative lies in CHP units permitting flexible multi-fuel operation, especially those which can be powered from locally available waste products or bioenergy such as landfill gas, manure, agricultural waste or willow coppice. Similar considerations apply to fuel cells working off reformer hydrogen generated from fossil fuels.

The principal research thrust on CHP is into exploring business and technical challenges to scaling down the technology and making its domestic and commercial deployment cost-effective. The large-scale deployment of such 'micro-CHP' is tightly linked to the electricity rate structures offered to consumers who own micro-generation plant. These rates determine how much they get for excess electricity injected into the grid.

Although they are often neglected within mainstream research, passive energy harvesting and energy-saving 'negawatt' technologies deployed locally are arguably cost-effective and efficient. Passive energy harvesting in the built environment makes use of smarter construction designs and materials, allowing natural means to heat, cool and illuminate buildings (Lovins, 2005). From an energy supply security point of view, these simple technologies are ideal because they can fulfil basic energy needs (essentially space and water heating) regardless of what happens to central energy networks. They also provide energy services with very limited environmental impact.

Advances in power electronic devices, converter design and control are stimulating the development of decentralised energy harvesting (Blaabjerg et al., 2004; Van Wyk and Lee, 1999). These technologies are needed at the interface between renewables and existing electrical networks. Over the past decade, technologies originally developed for variable speed motor drives have been adapted to provide power conditioning modules for wind turbines. Mass production of fast and increasingly efficient semiconductor switches, insulated gate bipolar transistors and gallium arsenide devices, for example, have made this possible. Current research focuses on decreasing device manufacturing costs even further and increasing their power-carrying capabilities.

2.3. *Energy demand and utilization*

Rare and momentary disruptions in energy flow can have serious consequences for economic and human activity. Over the last half-century, however, centrally structured systems have generally been quite successful in providing consumers with a continuous and reliable flow of energy. Consumers enjoy relative isolation from abrupt, short-term ups and downs within the energy supply chain. This helps sustain society and the economy, but it has also rendered consumers inflexible and made them unaware of the impact of their energy use and their expectations of high quality energy supply. At the moment, there are few options available to consumers to be more flexible aside from their choice of an energy supplier. This situation, however, is increasingly expensive, and is technically challenging for either a decentralised or a central infrastructure.

It is agreed that a move towards an active demand side is valuable, and indeed necessary, if flexible networks are to become a reality (European Commission, 2006). Research in this area seeks to generate opportunities for enhancing demand flexibility, using dynamic shifting of demand in response to energy prices and other signals such as the availability of renewable energy. A collateral goal is to achieve these dynamic demand shifts transparently without significantly harming comfort and productivity. Technologies for making this happen, including demand-side energy management systems, smart metres and appliances, are starting to appear in the mass market. The pressing issues associated with these technologies are the standardisation and interoperability of equipment and software.

2.4. *Energy storage*

In a more decentralised supply system, especially one based on variable and intermittent renewables, localised energy storage can buffer temporary imbalances between the energy produced and consumed. There is also evidence that energy storage plant can be valuable in a centralised system, by helping to relieve network bottlenecks and in managing the intake of electricity from large-scale wind generation.

The principles here are not new, and the potential gains could be manifold if the energy conversion efficiencies and capital costs of mass-produced storage systems can be brought down further.

2.5. *Network design and control, operational paradigms and ICT*

Future electricity networks will need to be sufficiently flexible to adopt the best configurations and modes of operation possible. It is also clear that the current hub-and-spoke transmission and distribution networks may not be ideal for integrating massive amounts of decentralised and variable generation. Likewise, the rather passive control schemes used to operate today's networks are too rigid to exploit the flexibility offered by energy storage, responsive demand, and central as well as dispersed generation (Fig. 1).

This is why considerable research effort is devoted across the industry and the academic community to develop the concepts and the tools needed to design and operate future grids, large and small (Djapic et al., 2007; European Commission, 2007; Hatziargyriou et al., 2007). For brevity, we shall only mention the concept of the microgrid (Hatziargyriou et al., 2007), which is seen as one of the possible network design and operation paradigms for decentralised electricity supply systems. Its salient feature is its ability to operate either connected to a wider network or as an island. This research is driven by the need to remove as many as possible of the technical barriers to seamless systems integration and flexible active network management.

In making this flexibility ideal a reality, there are two technical preconditions. Coordinated research and standardisation efforts are still needed to devise the open and robust ICT infrastructure and protocols required to support the safe operation and the active management of future electricity networks. The commercial playing field also needs to be levelled by adopting industry-wide open standards for the interconnection and operation of grid-connected dispersed generation and network plant, creating a true plug-and-play architecture. This should spur further innovation and shorter time to market for new technologies. The hope would be for this standardisation effort to parallel the success generated by the adoption of the GSM standard in the mobile communication industry. These are mainly issues for industry, with the research community providing the scientific basis for the standards that are adopted.

2.6. *Managing the transition*

A greater challenge still for the industry is the management of the transition between today's highly integrated and passive systems and those envisioned; see, for instance, the vision of the European Commission (2006) for this transition in Fig. 2. This transition is happening at a moment when a great proportion of

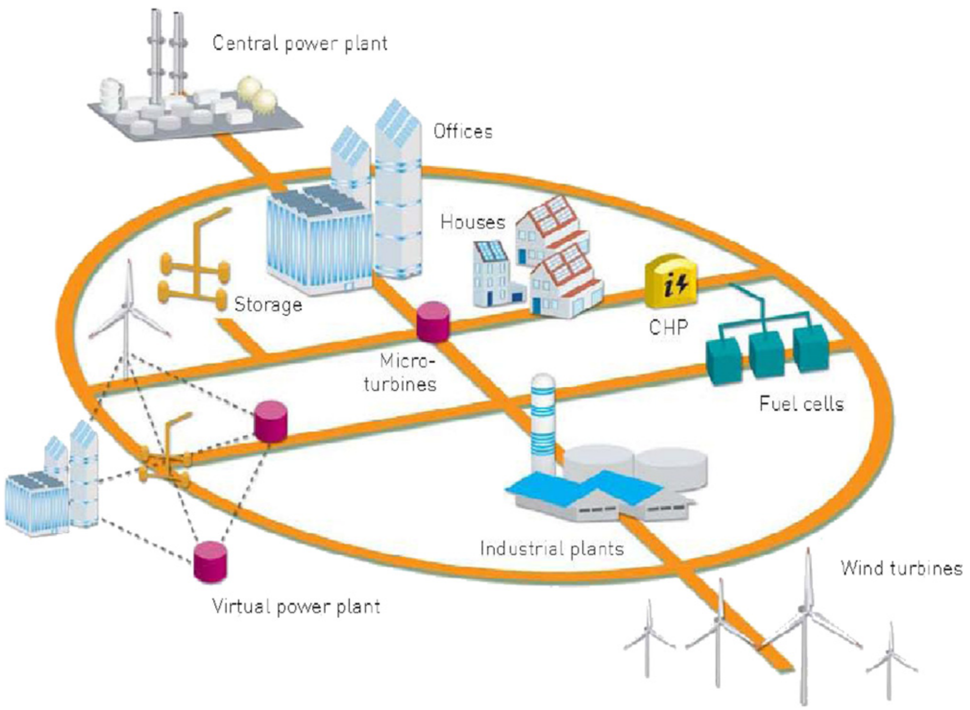

Fig. 1. Future grid integrating a variety of central and distributed technologies (European Commission, 2006).

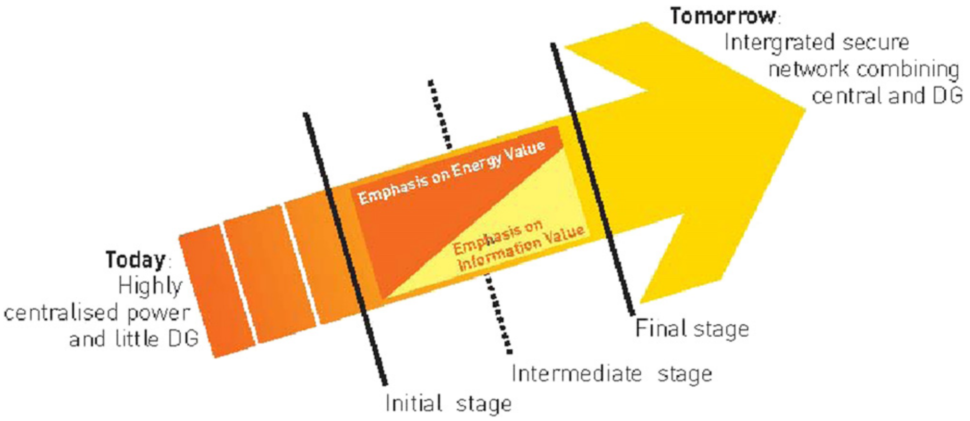

Fig. 2. Envisioned evolution of electricity systems under the European Technology Platform SmartGrids (European Commission, 2006).

the installed central generation, transmission and distribution plant is reaching the end of its usable lifetime. This could be seen as a great opportunity to modernise the supply systems and make them more resilient and flexible. The utility industry, however, is by nature conservative in the way it plans ahead and operates. It is generally reluctant to introduce costly new technologies unless tangible benefits can be readily demonstrated. The danger now is of the adoption of a ‘like for like’ plant replacement strategy, which could further delay the true emergence of more flexible systems.

The deployment of a more decentralised infrastructure should depend on individual investment decisions. In fact, the current development of dispersed generation is often driven more by altruistic and environmental motivations than pure economic business judgement, even though some evidence may suggest the opposite (Lovins, 2005).

Given that policy makers regard the development of a more decentralised energy supply chain as beneficial for society, they should provide the regulatory framework and the incentives necessary to make investments in dispersed system plant economically profitable.

This is why economic and policy research is looking at designing market mechanisms for valuing and managing the risks associated with energy supplies, network usage and flexibility within future networks. Meanwhile, social scientists are looking at how energy consumers understand the implications of moving to a more decentralised infrastructure and how they could engage more fully and positively with it by becoming increasingly flexible.

3. Future advances

We outline next the principal advances that may have the greatest impact on the direction in which electrical energy systems will evolve within the next 40 years.

3.1. *Self-regulating networks*

The flexible networks we envision here are only an intermediate step to the ultimate goal of having a highly autonomous energy supply infrastructure capable of bidirectional energy flow, rapid reconfiguration and adaptation. If standardisation and mass market penetration of advanced storage, ICT, demand response, networks and flexible generation happen, this will be close to reality. Because this advance requires massive investments in network modernisation, long delays in its full implementation are expected. The whole process could take until 2020–2030.

3.2. *Carbon capture and sequestration*

By 2020, carbon capture and sequestration may increase the importance of centrally supplied energy. This technology is most probably not suited to decentralised implementation because of its complexity and cost. It works by extracting CO_2 from the flue gas of a power station or by gasifying coal to extract its carbon content before the remaining hydrogen-rich gas is used in the power station. In either case, the captured CO_2 is then stored. CO_2 capture and coal gasification processes are available, but significant uncertainty remains regarding the viability of sequestration techniques (Hoffert et al., 2002).

3.3. *Nuclear energy*

In the same vein, more aggressive research may establish nuclear energy (fission and fusion) as another driver for the maintenance of a strong central infrastructure. In the case of fission, significant uncertainties remain regarding current government policy and the need to raise sufficient capital privately to build new stations and develop new reactor designs (see Sidiqqi and Fleten, 2007, for the case of thorium-based technologies). There is also significant uncertainty about the long-term management and storage of nuclear waste. Fusion represents the better opportunity in the 2050 horizon and beyond, but significant research and investments are still needed.

3.4. *High temperature superconducting networks*

High temperature superconductivity is available today, but is yet to make a real difference in electricity grids. It will have more immediate positive impacts in the development of electricity storage. In the long run it may also be used in long-distance power transmission, for example in superconducting cables and transformers. Once capital costs are brought sufficiently down, in the horizon of 2030, superconducting grids moving power in bulk across continents could start to be envisaged. This is the antithesis of decentralisation. It represents an opportunity to better pool energy resources across wide areas, smoothing out uncertainties and levelling off the utilisation factors of generation and network plant.

3.5. *Hydrogen economy*

The realisation of the hydrogen economy has been the Holy Grail of energy research in the 21st century (Rifkin, 2002). The generation of hydrogen from wind or photovoltaic-powered electrolysis will provide a way to buffer the variations in these carbon-free energy sources and produce a clean fuel for transportation. The infrastructure will be developed centrally to begin with and may then be deployed in a dispersed fashion as costs are driven down. The initial deployment needs a grid capable of pooling both energy demand and supply. In the longer term, this infrastructure may no longer be needed as smaller-scale equipment becomes viable. But, as with any emerging technology, realising economies of scale and maximising efficiency and the use of existing infrastructure will be preconditions for commercial success.

The outlook for commercial success in 2050 and beyond depends on the resolution of many technical problems. These include serious safety and technical concerns with the storage and transportation of hydrogen.

4. Concluding remarks

This review paper has identified the drivers behind the ongoing mutation of energy supply infrastructure, with a particular focus on electricity. Climate change and declining fossil fuel reserves are motivating the emergence of renewable and more distributed and efficient generation technologies. This begs the question of the relevance of a centrally operated electricity generation, transmission and distribution infrastructure up to 2050 and beyond. The current and the future science calls instead for a hybrid but, most importantly, flexible infrastructure which will be adaptable and reliable, and so will deliver the maximum welfare to society in a sustainable way.

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