SIEMENS

Ingenuity for life

Cooperation

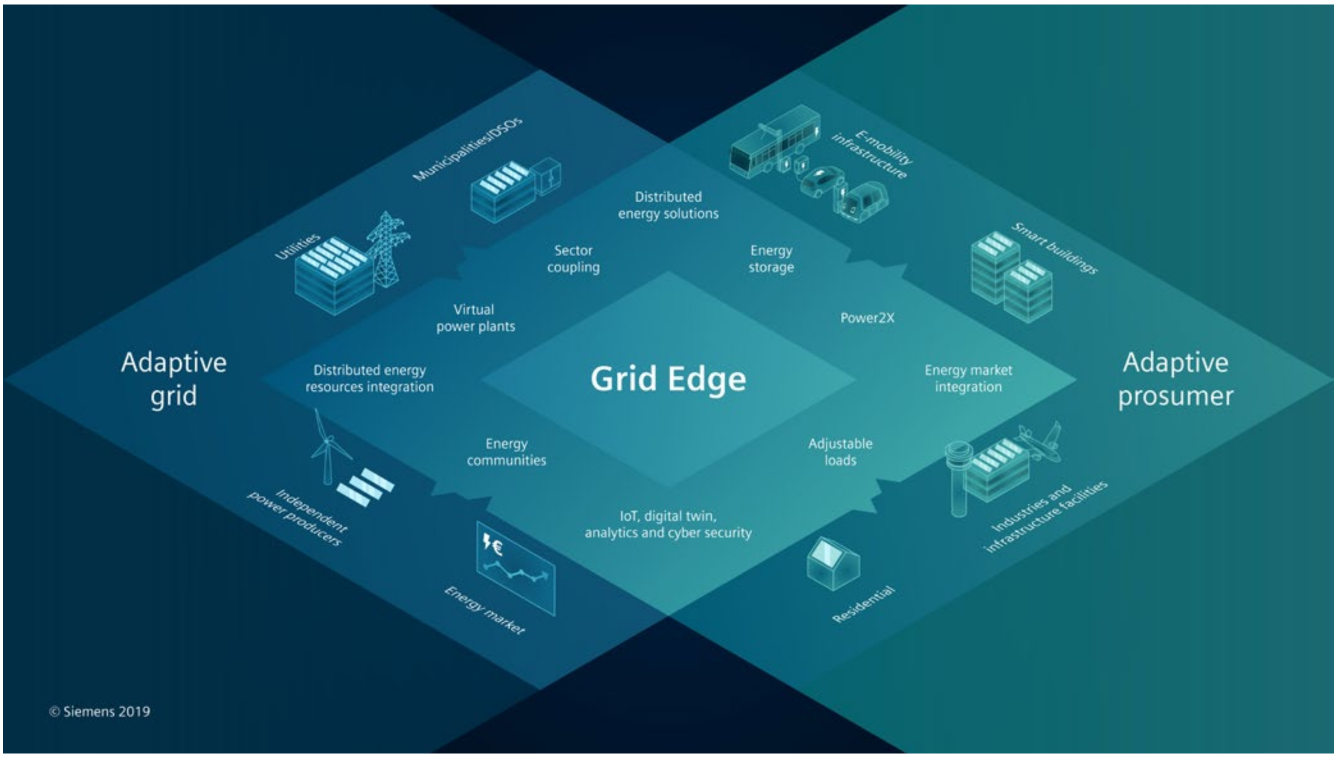
UNIVERSITY OF OXFORD

TU berlin

The grid edge revolution

Innovative drivers towards net-zero energy

siemens.com/smart-infrastructure



The grid edge: definition and significance

The original definition of the grid edge was "the interface between the grid and the end-consumer or final customer". Today, the meaning of the term has become broader and refers to the many connected technologies that exist between the energy supply side (grid) and the energy demand side (building, industry, and consumer). These technologies include those for local consumption and production as well as for the storage of electrical energy. Beside the primary technology for coupling electricity with other forms of energy to satisfy the need for temperature, mobility, mechanical power, etc., it also covers ICT technology such as smart meters, energy management systems and specific solutions such as eMobility charging and battery storage.

Innovation in both hardware and software can be found at the grid edge. Hardware includes solar panels, advanced metering infrastructure, smart inverters, energy storage systems, smart thermostats, smart appliances and building controls. Software includes automated price-responsive demand response, real-time grid optimization, data analytics, and integrated distribution system planning systems.

It is at the grid edge where a significant change is taking place. Historical power systems had evolved as highly centralized top-down systems, connecting large power stations to a passive demand side on the edge of this grid. Today the grid edge becomes active and consumers become prosumers by feeding power into the grid or managing their own system with their own storage. As a result, some grid users already have a net-zero energy system. However, the grid is still required as backup and to trade electricity with other grid users.

The grid edge revolution Introduction

Our way of life is dependent on abundant and reliable energy supplies. Energy helps to give us warmth, mobility and food as well as satisfying our need for information and communication. It has helped to drive huge advances – most recently in computing, networking and social media. But this development has come at a cost, particularly in terms of CO_2 output and climate change. Today there is public and political pressure to move quickly, to radically reduce carbon emissions, and to achieve net-zero energy.

At the same time, recent technological developments – including AI and data-driven systems – are creating new forms of connectedness and are opening up new opportunities for the way the world generates and uses energy. These advances are helping to make multiple, small and green energy sources more viable, and to create more efficient trading. These developments are helping to give people greater control over their energy use. In time, they will decouple service and use. At the heart of this transition is the grid edge – the interface between the grid, the final consumer and the technologies that connect to it.

This whitepaper examines developments at the grid edge and their impact on the transition to a net-zero energy system:

Section 1 covers the social implications of this change. It examines the phases of the transition and the drivers behind it – notably the 5Ds of decarbonization, decentralization, decoupling, digitization and democratization.

Section 2 looks at the technologies and business models involved. It examines the business case for owners and the potential risks of such a transition.

We show how innovations at the grid edge are helping to drive one of the most radical transitions in human history – a move from a centralized energy system to one that is more decentralized, more local and more efficient. Towards an energy system that is more democratic and where individuals have more control; an energy system that meets the needs of the global population but that also benefits the planet.

Section 1:

Social implications of a net-zero transition

1 Introduction

It is likely that the human population of the world will still have very similar basic energy needs in 2050 – warmth, food, mobility and connections – despite ongoing changes in technology. A successful transition to a low-carbon world could therefore be characterized as continuing to provide much the same energy services for those who already enjoy them while bringing billions of people in developing countries up to the same standard.

In this section we explore how developments at the grid edge can maintain our way of life while supporting the fundamental changes in energy that the world needs. And it looks further to explore how, with well-considered ingenuity, improvements can be made to address societal needs that wouldn't even be considered part of the power system.

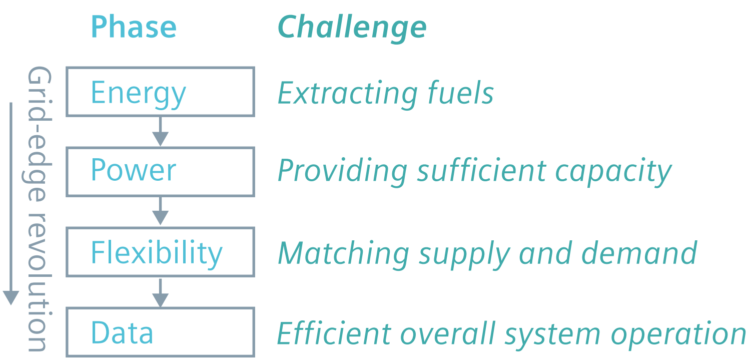
We examine how more distributed generation and storage enable more local solutions, new trading platforms and markets that can give people choices like never before, and how the democratization of data allows new levels of control for everyone. The result is an energy system that genuinely empowers people across the world – and what is happening at the grid edge is absolutely fundamental to this.

2 Four phases of transition

The focus of effort in global systems of energy provision is undergoing a profound shift that is nothing short of a revolution. The transition of global energy systems can be characterized in four phases. The first phase is about energy itself, the second phase, which we are currently experiencing, is about capacity. The greatest future opportunities, however, lie with new and emerging challenges in phases three and four: flexibility and data. Here we briefly review the drivers behind the shift in emphasis of each phase, which transport us from a centralized model right to the edges of the grid.

Figure 1:

Four phases of energy transition and key challenges.



2.1 Phase 1: Energy

Historically, the greatest effort in energy generation was spent on sourcing the fuel. Early urban dwellings were limited in their size by the range from which wood could be sourced from local forests. More recently the extraction of energy from deep structures, such as coal mines or oil fields and subsequent transport to the point of demand, has dominated the cost of energy. Due to the excellent storage properties of these fuels, little effort is required to make their energy available as required to meet demand. The predominant cost of energy during this first phase is in the production of the fuel rather than its storage or conversion. This holds true even where significant exploration budgets are involved.

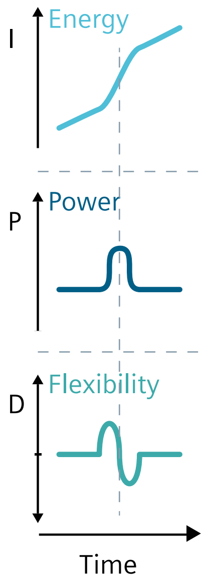
2.2 Phase 2: Power

The transition to distributed renewable sources, which we are currently experiencing reverses this effort. The extraction no longer requires effort, but mere capital expenditure to build the capacity, which turns natural resources into power. Once renewable assets have been financed and deployed, the cost of generating electricity is negligibly low. Wind and sun present themselves 'for free'. The cost structure of high upfront capital expenditure with low running cost is not new in itself. Nuclear power stations exhibit a similar relationship between power and energy cost, which has led to the need for new financing models, often in need of state level support. What makes renewables fundamentally different is their scale. The ability to produce and deploy photovoltaic (PV) panels at anything from kW (household level) to MW (small power station) scale has led to deployment without the need for state-level finance (subsidies notwithstanding) and the private sector is able to accelerate uptake. At the same time, scale-up has led to the dramatic reductions in manufacturing and installation costs witnessed for both wind and solar.

2.3 Phase 3: Flexibility

Figure 2:

The relationship between the first three phases of transition: From energy to power and flexibility. Data helps to manage and control the relationship between these three.



Relationships	Unit	Requirement	Example
$E(t) = \int P(t)\,\delta t$	W h	Resource	Fuel
$P(t) = \frac{\delta}{\delta t} E(t)$ $P(t) = \int R(t)\,\delta t$	W	Capacity	Plant size
$R(t) = \frac{\delta}{\delta t} P(t)$	$\frac{W}{h}$	Responsiveness	Load change

The cost of integrating renewables into a functional, reliable and affordable system increases and becomes more challenging the larger the share of solar and wind in the overall portfolio of generation. The dramatic fall in the costs of renewable energy and its rapid deployment is challenging existing systems and market structures[8]. This has two reasons: 1) many renewable sources of electricity have negligible running costs and 2) their output is less controllable than the sources they displace[6].

Much is made of the second point in public debate, but it could be the less important of the two[12]. Variable supply is no different from variable demand in a system context and systems always had to cope with variable demand. Grünewald and Torriti[7] found that load profiles have become less variable over the past 30 years and the ratio of peak to mean demand has fallen. An increase in net-load variability therefore does not constitute a fundamentally new challenge. Furthermore, it is technically possible to control output (at least downwards) by curtailing it. For sources with no short-run marginal costs this does not even carry an economic penalty. However, policies rewarding energy output (such as feed-in tariffs or renewable obligation certificates) create a commercial disincentive and in the public discourse such curtailment is often wrongly presented as wasteful or inefficient[9, 6].

Electricity is a highly unusual commodity in that supply and demand have to be kept in balance in real time. Changes to load require almost immediate responses. Conventional, centralized systems have four mechanism by which they keep this balance:

1) flexible generation

2) large grids

3) storage

4) flexible demand

Flexible generation relies on two properties of fossil fuel-based power stations. Firstly, their design involves significant rotating mass, giving them inertia. Secondly, the fuels they use are easy to store and therefore usually abundantly available for a power station to ramp up as required.

The diversification of loads and stochastic use of electricity has a smoothing effect on load profiles. The larger the network the less likely sudden load changes become and the task of load following becomes easier. If, for instance, 10% of users were to spontaneously decide to start their washing machine at the same time, most systems would not be able to cope due to the rate of increase, even if sufficient power station capacity were available. Synchronization of use over short time-scales therefore poses a particular challenge. Examples are live TV events and other societally coordinated activities, such as public celebrations.

The immediate response mechanism in many conventional power systems is not one that was deliberately or purpose-built. It is rather a fortunate side effect of thermal power station technology having its roots in heavy engineering. The steam turbines that drive the generator shaft in thermal power stations are of considerable size and weight and therefore possess significant inertia. All thermal power stations operating on an AC grid have to operate synchronously at the same frequency. In most systems this is either 3,000 or 3,600 rpm (50 Hz or 60 Hz respectively)[6].

A sudden load change adds or removes force from these rotating masses, thereby slowing them down or speeding them up and changing the grid frequency. The change in frequency is a form of immediate storage using the angular momentum of rotating mass. Reducing the speed of turbines across the system releases stored energy to the grid, whereas speeding them up is a way of storing temporarily surplus energy from the system. Strictly speaking, the change in frequency isn't even a system response as such. No one had to react. Rather, the rotating mass is inbuilt inertia that stabilizes the system in a passive way. The more such inertia (mass) is present, the less grid frequency changes in response to load changes.

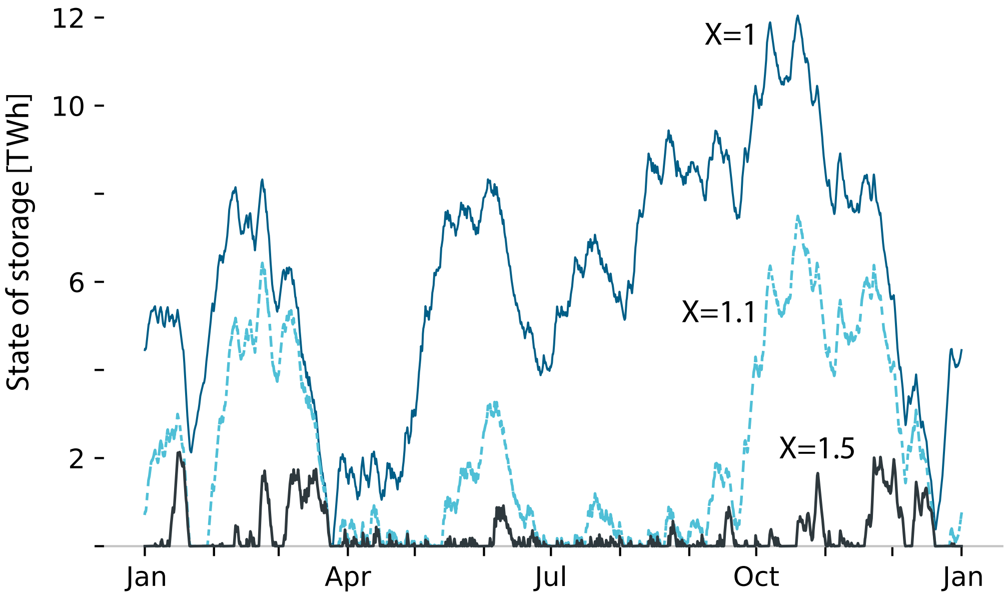
The second mechanism is the scale of the grid. The larger a grid infrastructure, the more power can be arbitraged in space. In addition to the load smoothing effect of larger grids, they also facilitate the connection of more diverse sources of generation. Weather systems typically span only a few hundred kilometers, such that interconnections between national systems can help balance regions with high or low wind or sun[11]. The benefit of diversity of sources also extends to national differences in the type of power stations, such as countries with higher shares of nuclear or geographies that are more suitable for hydro or even pumped-hydro generation.

The move towards a low-carbon system changes the balance between the four mechanisms of flexibility. The displacement of fossil fuel plants reduces the flexibility of generation and the move towards more localized solutions requires greater abilities to balance greater volatility across potentially smaller grids.

Storage and flexible demand may have to contribute greater shares of flexibility. Batteries are already used to support short-term variability, replacing lost inertia. However, longer storage durations and significant bulk storage may be required to deal with seasonal variations in supply and demand. A vast array of resources may be required to replace lost flexibility with to aim to maintain similar levels of supply reliability. As *figure 3* illustrates, unless excess amounts of renewables are installed, significant amounts of storage may need to be held for considerable durations. The annualized investment costs of such a system could amount to an unpalatable €2,000 per citizen.

Figure 3:

The counter-intuitive case of excess generation leading to lower system costs, reduced storage requirements and shorter storage duration. In general, load reshaping may critically reduce the remaining storage requirements.



The alternative is a smarter integration of generators and loads. Alongside storage and expansive networks, changes to demand itself may be required. This can be facilitated with technological innovation and in particular with better use of data.

2.4 Phase 4: Data

Compared to other sectors, energy is remarkably data poor. This is ironic, given that every appliance on a power network is 'connected', but as yet unable to communicate. Even at network level, access to data is extremely limited. While high voltage networks are actively managed, most low-voltage systems are entirely passive. Neither load nor voltage or even phase imbalances are known to network operators, who tend to rely on sufficient amounts of copper to ensure a certain level of supply. The opportunities for data to improve system operation are significant.

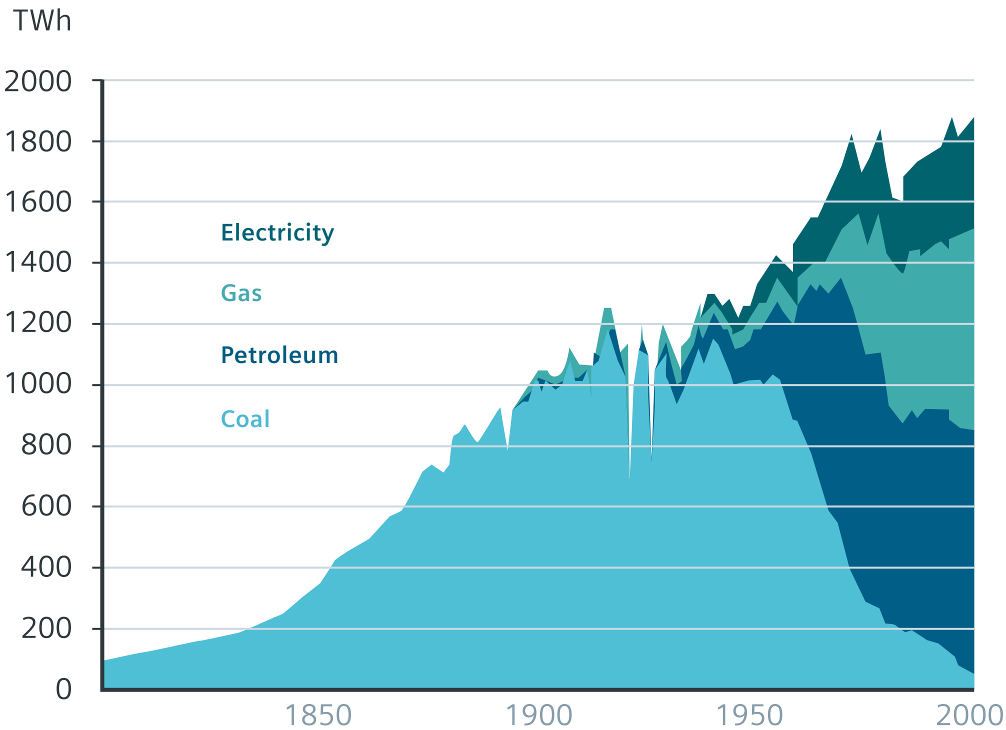
The enhanced use of data in energy will span a wide range of domains – from sensors on the networks, to smart meters, but also to valuable data from appliances and users themselves. This data will support the assessment of the state of a system, plan operation and upgrade requirements, improve load prediction in real time, manage supply shortfalls with minimal service impact, improve service experience of customers and even provide the intelligence to help reshape loads to better suit the predicted patterns of supply.

As such, data underpins all of the previous three phases. It helps optimize and manage energy flow, it improves utilization and reduces the need for power, and it enables and enhances the access to sources of flexibility in the system.

3 Sector coupling

Figure 4:

Transition of fuel types in the past 200 years in the UK. Source: Fouquet[3]



The emergence of the main primary sources of energy shown in *figure 4* has been followed by many developed economies. Wood has been complemented by coal, petroleum and gas in that order. Today, electricity is the strongest growing vector with the greatest potential for decarbonization. Due to the versatility of electricity, it is expected to play an increasing role in displacing fuels in other sectors. Electric vehicles stand to replace petroleum as a transport fuel and electric heating may displace gas.

3.1 EV charging

Many manufactures have embraced the trend for electric vehicles and some advanced economies have set firm targets for the phasing out of combustion engines[10], which adds political certainty to this transition. Data on charging patterns of electric vehicles is not yet conclusive. Some studies have found that charging begins as people arrive home from work[3]. Others noted that the distribution of start times and charge duration results in the peak contribution to be later in the evening at around 9 p.m. Yet other research has found that many users with smart chargers are able to delay their load until later at night.

Smart chargers, commercial incentives and sufficient data to monitor and evaluate charging patterns could unlock potentially significant flexibility from these loads. Some envisage an even more beneficial interaction, whereby vehicle-to-grid solutions would discharge vehicle batteries at times when the grid requires short bursts of power, or even to load balance. Such operations need to balance the life expectancy of vehicle batteries with the relative utility value of driving and grid services.

Looking to the future, one should not be constrained by current mobility patterns. With the arrival of autonomous vehicles, the location and the timing of recharging may change fundamentally. Instead of parking a vehicle near the destination of travel, autonomous vehicles are free to relocate to a convenient grid point and form part of the grid infrastructure until requested back for mobility services. New business and ownership models with implications for mobility patterns are likely to emerge as a result, such as the sharing economy, which is an early adopter of electric vehicles for car clubs.

3.2 Electrification of heat

The transition away from gas is less clear. The decarbonization of heat in particular remains a policy challenge without simple solutions. Here, too, electrification with heat pumps or night storage heaters is a technical possibility, but many challenges and commercial opportunities remain in this transition. From an electricity systems perspective, this coupling of sectors is particularly interesting. Depending on the climatic conditions, new stresses can emerge or existing stresses become exacerbated.

In cold-temperate climates, electricity and heat demand are positively correlated. Electrifying heat can add demand to critical peak demand periods, which may require costly expansion of generating capacity and particularly expensive distribution network upgrades. Similar effects may be experienced in hot climates with the emergence of air conditioning. They may be partially mitigated with positive correlations with PV output.

Heat pumps have been favored as an alternative to gas in some regions and jurisdictions, but the policy landscape in still inconsistent in their support. The load pattern of heat pumps is more continuous than that of conventional boilers, leaving less room for temporal flexibility, especially on critically cold days that tend to coincide with peak demand. An unintended consequence of the reduced coefficient of performance during a cold snap could be the use of resistive heaters as backup, which could exacerbate peak loads even further. Careful management of heat loads could therefore be vital, including the consideration of thermal efficiency of buildings and thermal stores.

An additional opportunity is the combination of technologies that could prove complementary. Dodds et al.[1] pointed out that distributed gas-powered combined heat and power (CHP) systems lose their carbon benefit once grid emission factors fall below 300g CO_2 per kWh. However, they proposed that systems powered by clean sources of gas could have a load-smoothing effect if deployed alongside heat pumps as shown in *figure 5*. They may also support the integration of electric vehicles as shown in *figure 6* for currently dominant charging patterns.

Figure 5:

Load duration curves for homes heated using: (i) natural gas (baseline), (ii) 20% of gas boilers replaced by heat pumps, and (iii) 20% heat pumps and 50% micro-CHP fuel cells. Data is based on measurements in 46 dwellings.
Source Dodds et al.[1]

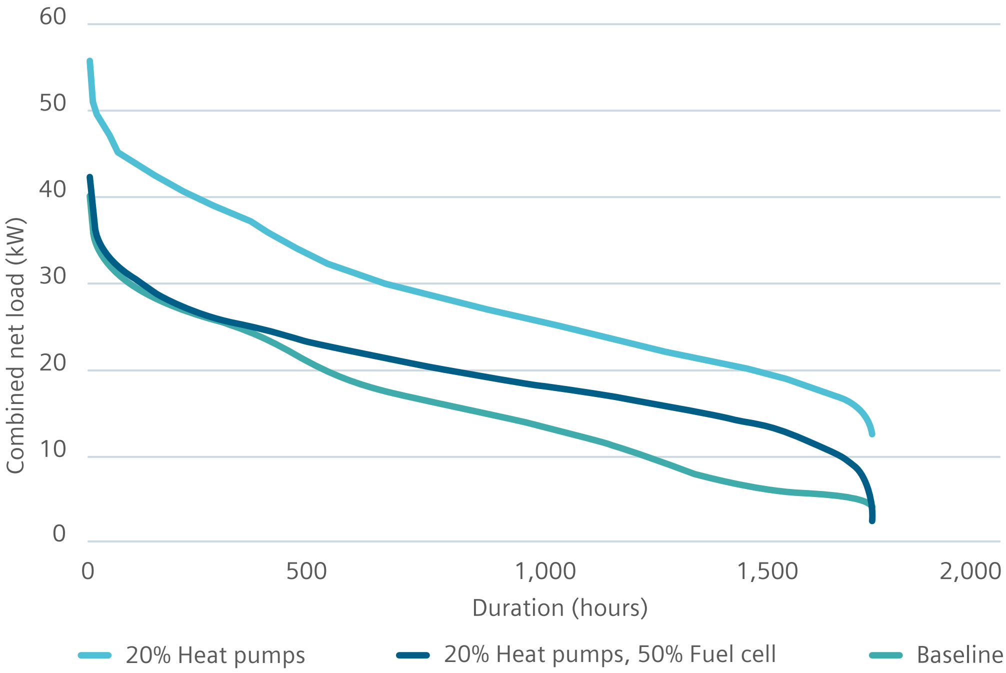
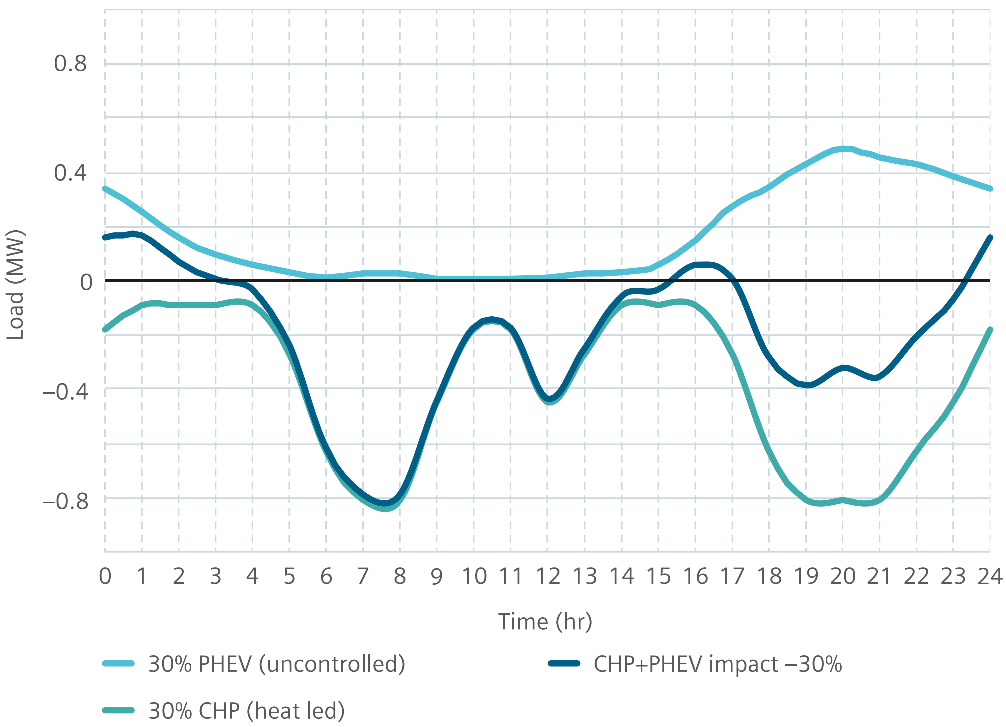


Figure 6:

Fuel cells can compensate for the evening load increase from PHEVs on distribution networks.
Source Dodds et al.[1]



4 Cost and economics

To appreciate the shift in the economics of energy it is worth focusing on two distinct costs: capital cost and operating costs. Conventional fuel-based systems are dominated by operating costs. The cost of constructing of a power station is often exceeded by the operating costs, such as for fuel, staff and maintenance, even when these are discounted. This is reflected in most analysis and market designs that compare cost and price units based on energy (kWh or MWh).

4.1 Marginal cost of generation

Renewable resources have a fundamentally different cost structure that is almost entirely based on capital cost. The short-run marginal cost (SRMC) of renewables, the cost of producing one extra unit of output, is practically zero. This has profound implications for the operation of future systems and challenges some fundamental principles of current business models that implicitly assume:

a level cost of electricity can be established for each technology

all units of energy have the same value

In practice, future markets will have to accommodate very different forms of elasticity. While a thermal power station is price-sensitive and will only generate when wholesale prices are above its own short-run costs, renewable resources operate between two extremes: zero marginal cost when available and infinitely high cost when not.

4.2 Cost of capital

Due to a different cost structure, investments in renewables and many other low-carbon assets are especially sensitive to the cost of capital as well as uncertainty about future revenue streams. In coal- or gas-dominated systems, electricity prices often reflect fluctuations in the cost of fuels, thereby giving greater certainty to the estimate of net present value of an investment. For investments in low-carbon infrastructure, uncertainty over future revenue streams can be a considerable investment deterrent and can raise the cost of capital.

Various energy policies and more or less direct support or underwriting of risk have given national governments a strong role in strategic decisions in energy, especially in relation of capital-intensive large-scale projects, such as nuclear power.

The grid edge-led deployment of a low-carbon transition is more amenable to private sector-led investment. While the scale of investment may often be smaller, the bankability risk may be higher and other forms of financing and support schemes may be required to speed up deployment. National and international NGOs and governments are likely to continue to play an important role.

4.3 The value of forecasting

A reliable weather forecast is appreciated by many as an indicator of whether or not to take an umbrella. Future energy systems will rely on forecasts for functions that are more fundamental than avoiding getting wet.

A weather forecast itself is an important input to overall demand modeling. National models can make reasonable predictions based on past demand and weather forecast data. For future energy systems the granularity requirements for precision may increase dramatically. It is not enough to know whether the next four hours are likely to be sunny, but the movement of individual clouds may need to be tracked to avoid sudden voltage drops on local networks.

Conveniently, the installed generation capacity can serve its own data needs to some extent. With sufficient access to PV panel output data, the arrival of clouds and local fluctuations in output can be predicted with greater precision. Machine learning can even recognize repeating patterns such as shading on specific panels at given times of day and year. Similar learning is possible from wind-generated data. All this data from the new sources themselves can help to schedule loads, storage and other sources of generation.

Strbac et al.[13] estimate that improved four-hour forecasting can halve the integration cost for renewables. In addition to supply side forecasting, better insights into the patterns of demand can further reduce investment and operational costs. The opportunities to expand on the quality of forecasts and the detail obtainable on demand to be matched with supply is covered in the section "Digitization".

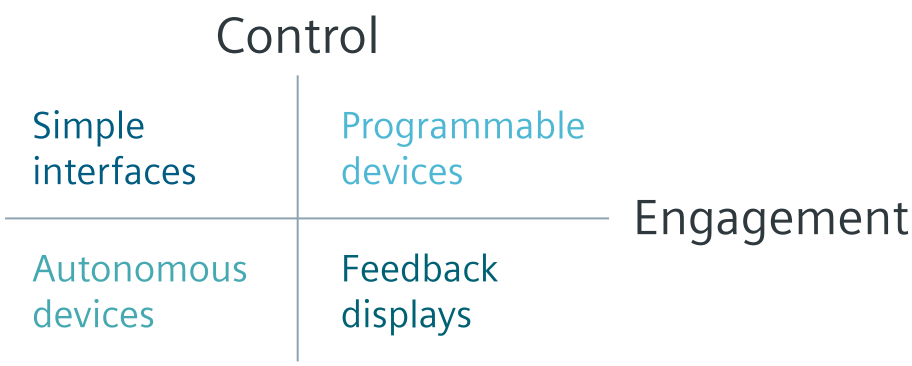
5 What customers want

We hold a wealth of surveys on public opinion on environmental issues, renewables, technologies, utilities, policies and governments. Two main lessons can be drawn from this body of evidence: 1) the public is broadly supportive of climate solutions and even willing to make sacrifices (typically more in the abstract than specific), 2) public views are complex and multi-dimensional. The latter point does not undermine the former. Rather, it challenges us to develop more personalized solutions that map onto a diverse array of preferences.

A simple 2x2 matrix in *Figure 7* can illustrate the opportunities. One dimension by which people differ considerably is their level of engagement with technology and energy technology in particular. For example, someone may well be technologically savvy, but just not all that excited about their washing machine's operating cycle. Some people have a great need to be in control of all settings, while others much rather delegate such decisions.

Figure 7:

User preferences call for a diversity of solutions



6 Five Ds for transition to the grid edge

The future transition of the energy system is driven and enabled by fundamental developments in science, technology and society. Here we focus on five such shifts and discuss how they affect the grid edge revolution. Each of these has a profound effect in its own right and collectively they can affect the scale and rate of change by mutually reenforcing each other.

The first driver considered is decarbonization as a primary response to anthropogenic climate change. The low-carbon sources deployed in response to this challenge are likely to lead to more decentralized systems in which the timing of demand becomes more decoupled from the timing of the energy service provided. Underpinning this transformation is the emergence of digitization and unprecedented access to and use of data. Finally, we argue that these trends have the potential to lead to greater democratization of citizens in their access to and choices over power.

6.1 Decarbonization

Decarbonization is becoming an increasingly strong driving force for changes to our energy systems. 'Peak oil' concerns have largely abated, yet the strength of climate science now makes decarbonization of energy a strong societal, policy and commercial driver. Recent publicity and public protests, such as Fridays for Future or Extinction Rebellion, have raised the pressure of public representatives and organizations to act and to be seen to act.

The focus is mostly on CO_2 reductions. Other environmental factors also drive a wide range of opportunities. These include air pollution, which leads to an estimated 4.2 million premature deaths globally every year. Further consideration needs to be given to resource depletion, biodiversity and intergenerational equity.

The new development is that decarbonization is no longer seen as an incremental change that can be achieved with gradual reductions in emissions. Especially in the context of other, harder to decarbonize sectors, such as aviation, the IPCC conclusions suggest that electricity would have to achieve net-zero in a matter of decades. This is not a gradual change but a reinvention of conventional systems. While many details and developments are as yet unforeseeable, some common points of agreement exist between most decarbonization scenarios. They comprise large shares of renewables. The significant requirements for storage and potential changes to demand itself have emerged more recently.

It is worth noting that feedback effects exist between environmental and energy systems. In recent years BP observed an increase in demand that was explained by more extreme weather events. Periods of heat increase the use (and deployment) of air conditioning, while cold snaps lead to higher heating loads. In this sense the decarbonization of energy systems can itself be seen as a demand reduction measure.

6.2 Decentralization

The switch from DC to AC transmission at the start of the 20th century led to significant economies of scale. Local DC systems of sub-MW scale were superseded by central power stations reaching in excess of 1 GW and connecting to a high-voltage national grid to feed every corner of the system. These economies of scale are now superseded by economies of numbers. Moore's law, or more accurately Wright's law, applies to solar photovoltaic in a way that has reduced the cost of unit production as the total installed capacity increases.

In some regions distributed solar power has broken parity with centralized fossil sources and this trend is expected to continue. This opens new possibilities for serving local demand with local resources, thereby bypassing the need for a national grid. Several benefits have been cited in the energy literature, including relative ease of financing smaller investments, including with community share offers and other participatory models. Local ownership has also been found to reduce resistance towards developments and enhance engagement.

The dynamics differ depending on whether or not such a grid infrastructure already exists. In developed electricity systems, distributed generation, especially when coupled with storage, can lead to apparent grid defection. Many small investors claim to be motivated by self-sufficiency and independence from the grid.

As *figure 8* illustrates, this is an expensive route if taken to the extreme. The peak power that has to be met for individual customers is significantly higher than a collective peak. In many cases the concept of self-sufficiency is therefore only partially realized. In practice, the grid still provides a backup function to ensure security of supply. Current market arrangements, which charge grid costs per unit energy (kWh) fail to recoup the appropriate value in this model. A nearly self-sufficient customer may only pay a fraction towards the system, yet still requires much the same power provision at times of local shortfalls. Rather inequitably, the socialized cost for the grid infrastructure is borne disproportionally by customers who may not be able to afford greater self-sufficiency.

Where such national infrastructures don't already exist, an alternative development pathway may be advantageous. In the section "Developing countries" we discuss how some regions may leapfrog the high-voltage grid-based approach and develop highly distributed solutions from the start. As demands for energy grow, the scale of such networks can be built out by connecting microgrids to each other. Because each microgrid is initially built to self balance, the flows between networks may remain relatively small compared to a conventional centralized system. Investment in such assets is therefore likely to remain lower than in the conventional model.

Even in a decentralized low-carbon system, large networks can continue to provide a range of benefits. Their role may change from the primary delivery of centralized power to one of facilitating regional and intraregional imbalances of power. In this role the utilization of some networks will be lower and new market arrangements for their appropriate remuneration may be required to reflect their role as a facilitator of flexibility and security of supply rather than a bulk carrier of energy. It will be important to value the services of these networks correctly, if stranded assets or unnecessarily large power capacity deployment is to be avoided.

Figure 8:

Diversification of users reduces the peak power requirements. Around 100 users are sufficient to achieve most of the diversification effect.

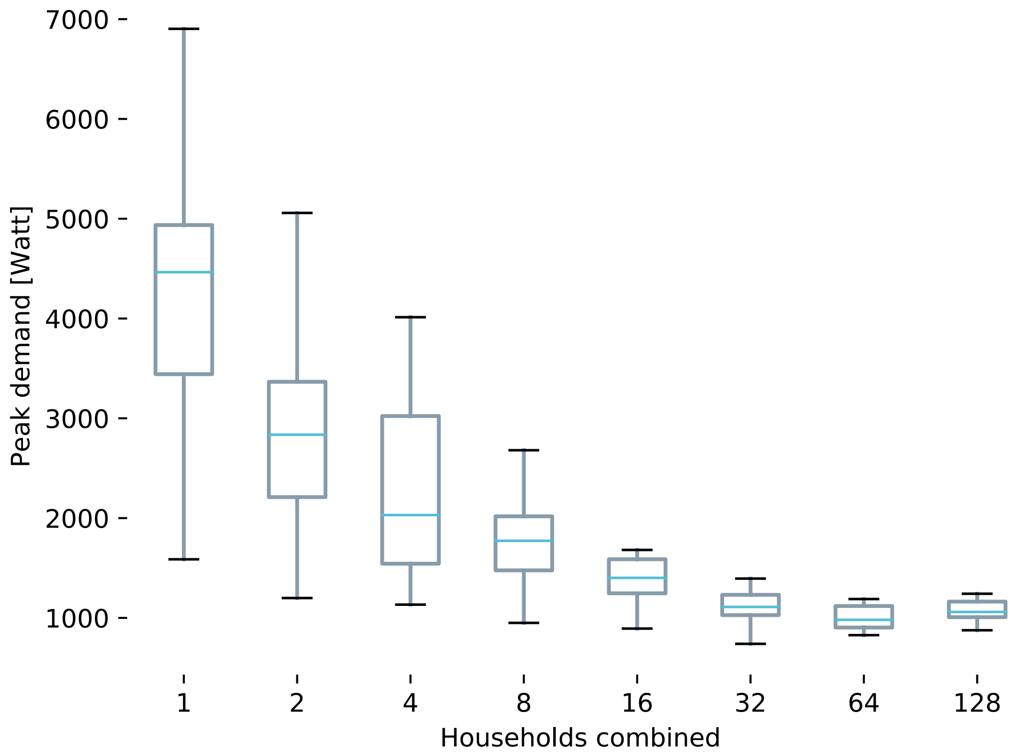
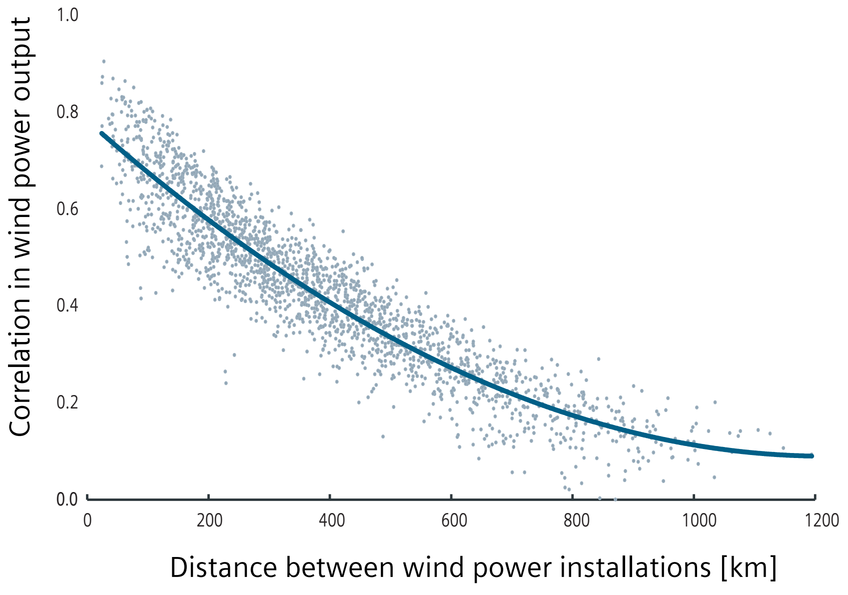


Figure 9:

Larger networks can diversify supply as shown here for GB wind data[11].



6.3 Decoupling energy service from energy use

One of the challenges of an electricity system is to match supply and demand in real time. In many cases this demand for energy coincides with the demand for an energy service. Operating an elevator has an instantaneous energy requirement that may need to be served at a particular moment. Other uses of energy may be more decoupled in time, especially if storage in the widest sense is present. For example, a chilled warehouse has a constant demand for cooling. Depending on the tolerance of the temperature range and the thermal mass (storage), the timing of the operation of the chiller unit can be more or less flexible.

Greater tolerances and more insulation or thermal mass can increase the flexibility, allowing a heater or a chiller to be left off for longer before the tolerance bands are reached. For this resource to become accessible for grid services, these states need to be monitored and communicated with data. For instance, for a hot water tank to be able to suspend its heating cycle, the volume of hot water needs to be known. If the owner runs out of hot water during the next shower, then their energy service expectation may not have been satisfied and future engagement with such services will be less forthcoming. However, if an AI system can develop some confidence about the shower patterns of this occupant, the range of response provision can be enhanced.

The effect of efficiency on flexibility is non-trivial. In the above example, a more efficient heating system is more flexible. In other cases, such as a refined industrial process that operates 'just in time', there may be high efficiency but little flexibility. Efficiency measures that reduce peak demand, such as energy-efficient lighting, relax some flexibility requirements, whereas efficiency in baseload appliances can make the volatility of the remaining profile appear greater.

The timing of washing machine load is governed by the availability of the operator and future requirements of clean laundry. If sufficient clean laundry is still available (storage), then a washing machine cycle can, in theory, be delayed within the temporal tolerances of the user. This could be facilitated with smart features, such as timers and two-way communication with the state of the energy system. Instead of running the load immediately, it can be scheduled within agreed hours.

The technical opportunities to exploit existing tolerances has only just begun – be they comfort levels, or sequencing of activities, or service expectations. Some aggregators are able to offer the combined response service for a portfolio of responsive loads as a grid service[5]. This resource can be enhanced the better it is understood with data. The implicit forms of storage are in many cases significantly cheaper that the cost of storing the equivalent amount of energy.

Some aspects of modern life already decouple energy demand timing from energy service provision. Mobile devices replacing TV screens perform this step in several ways. Firstly, a mobile device is more energy efficient than a typical TV set it replaces. Secondly, the timing of use of the device and the time of electrical demand on the grid (charging) no longer coincide. And thirdly, even the use itself has become somewhat more flexible in time, since on-demand content no longer synchronizes societies to a given television schedule. Many other services may still become decoupled in similar ways.

The investment decisions in relation to demand flexibility can be challenging for customers. Neither future price volatility nor an individual's own ability (with or without technological aids) to be flexible are well understood in advance. This is where AI solutions may advise users on their options trained on past usage and learned preferences, such as risk-reward characteristics, discount rates and financing ability. Complex choices between efficiency measures, storage, self-generation, tariff choices and supply reliability would be too much for most end-users to evaluate. Well-designed software can reassure and guide customers through their options. The more data the software can build its recommendations on, the better these become.

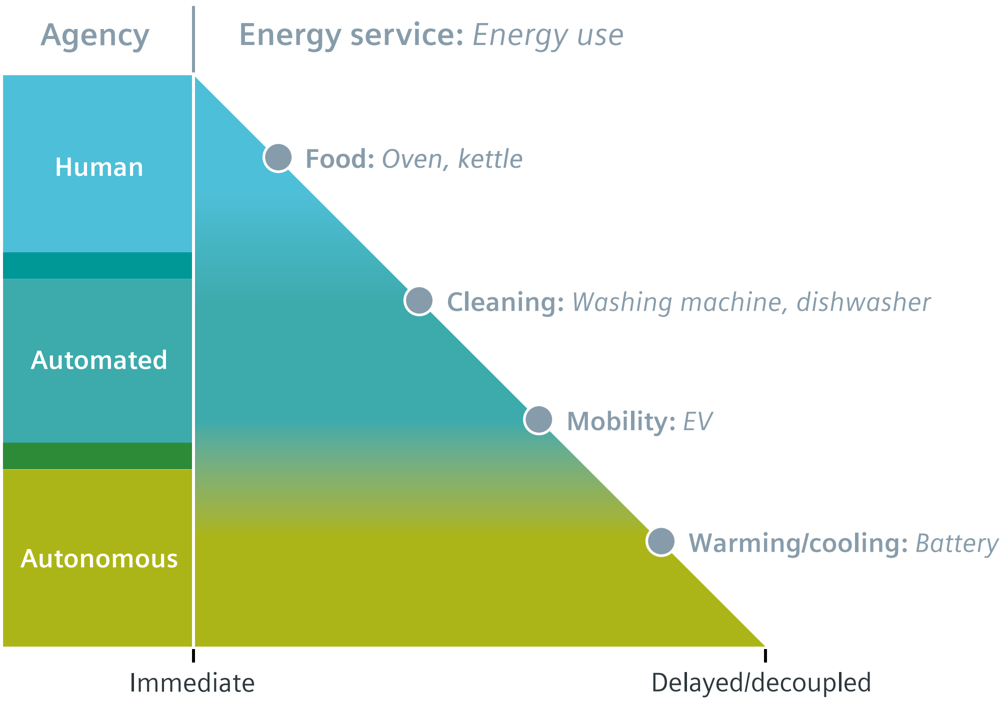


Figure 10:

Three levels of agency to decouple service provision from energy use in time.

6.4 Digitization

As previous sections have hinted at several times, any of the trends in energy are underpinned by data. Data about energy resources and their likely future output, data about the state of the network, and increasingly rich data about demand, appliance use and possible resources for flexibility in demand.

The operation of the multitude of assets described above would not be possible without the availability of new levels of data and control systems. Digitization in energy is at an early stage and likely to transform future transactions. As a first step, smart meters will support time-resolved settlement.

6.4.1 Smart meters – essential or redundant?

Any business model seeking to value the timing of demand requires a trusted means to establish when demand occurred. Many metering infrastructures, even in highly developed countries, date back over 100 years. A mechanical counter is manually read out by a meter reader in person, walking from house to house to gain access to often inaccessible devices. Such readings take place too infrequently to infer timing and too irregularly to even evaluate reliable seasonal patterns.

Smart meters are a significant improvement on this state of affairs but not universally greeted with enthusiasm. Privacy, trust and cost concerns are among the public reactions to mandated and commercial rollouts.

Among the claimed benefits for utilities are:

- ***more reliable billing***
- ***fewer complaints about misread meter readings (i.e. fewer call center staff)***
- ***savings on meter reading staff or contractors***
- ***ability to remotely disconnect customers failing to pay their bills***

For end users the claimed benefits include:

- ***accurate billing***
- ***better feedback with in-home displays***
- ***saving resulting from this awareness.***

The scale of these benefits has been reviewed in literature but remains somewhat uncertain. The long-term benefits for a smart meter infrastructure are more likely to be found in the data they provide and the new business models these enable. Time varying tariffs, such as time of use or real time pricing, are only possible if readings are taken with sufficient temporal resolution and at billing quality accuracy[4]. Default temporal resolution of the latest SMETS 2 smart meters is on the order of 30 minutes, although 10 second data can be accessed with additional hardware and user permissions.

In addition to new tariffs to encourage the use of electricity at times of lower cost (or to dissuade use at times of high cost), the data from smart meters can feed into increasingly powerful machine learning algorithms to improve load forecasting and develop a deeper understanding to flexibility in demand.

6.4.2 Beyond smart meters

In a fast-moving world of connected devices and an emerging Internet of things, smart meters may soon be only a small part of the sources of data available for grid services and other new business models. Every appliance can, in theory, broadcast its own consumption patterns directly to service providers and even receive instructions back to affect its demand patterns. The IPv6 protocol is designed to facilitate identification of appliances at this level.

This data is likely to support more sophisticated operations and the internet of things allows detailed assessment of particular energy service functions. Understanding the use patterns of different end-users allows us to pinpoint inefficiencies and even unintentional energy use, which is not uncommon, especially with poorly operated BMS and HVAC systems. Data beyond energy can be linked with this data for even richer insights. Weather or transport data can help to improve load forecasting. Machine learning from seemingly unrelated properties can yield new approaches to the reduction, re-scheduling or vector switching in energy demand.

The effective use of data can transform all three levels illustrated in *figure 10*. Feedback of data, especially if synthesized into actionable information, can help users improve their own decision making, either in their direct energy relevant actions or in how they take advantage of services that can be automated. The better the information and feedback provided, the greater the user confidence and willingness to translate their operational tolerances into system valuable flexibility.

Ultimately, users may take an increasing number of decisions towards fully autonomous systems. How much this transition is contingent on trust can be illustrated with public perceptions on seemingly benign applications. Fridges already use a duty cycle to periodically chill their contents. Industrial and commercial operators are quick to see and embrace the opportunities from handing the control to systems that can optimize the operating cycle. Surveys of private individuals suggest that they are suspicious of such solutions for the residential sector. Rendering control to mistrusted 'utilities' is perceived as risky. Only 30% of the UK public are in favor of such solutions. As a result, fridge manufacturers are reluctant to embrace 'smartness' for fear of suffering brand reputational damage if a customer should blame them for food poisoning. Reassuring customers with appropriate feedback and information based on high quality data can unlock the significant potential in this sector.

6.4.3 Advanced use of data

Energy data and complementary data stand to become valuable well beyond the energy domain itself. Patterns of demand can reveal a wealth of information. Abnormalities in profiles can immediately be acted upon with appropriate responses. For instance, machine learning and AI approaches can detect deteriorating health in elderly citizens – if they consent to such levels of observation. Or the decline of a household into fuel poverty can be detected in ways currently not possible so that mitigating measures and support can be offered in effective and targeted ways.

Commercial operators can monitor and be alerted to irregularities in operation that can act as an early indicator for equipment failure. AI approaches have been successfully deployed for wind turbines to provide such preemptive failure detection.

6.5 Democratization

The term 'power' has a dual meaning in the English language. As well as physical power, it can mean societal power. With the transition of power from the center of the system to the grid edge, both types of power can be considered. The decision what type of power station to build is largely politically driven and devolved to state or market. Individual energy users have a limited choice to express a preference via their supplier. This is exemplified by the current reduction of customers to mere 'consumers'. The term prosumer is meant to conjure up the additional function of consumers as producers of energy. But the transformation is more profound than this once decentralization, decoupling and datafication have taken hold.

In decentralized systems the choices available to individuals or groups and organizations wanting to take an active role over the sources of their electricity is greatly improved. Peer-to-peer trading solutions can facilitate specific bilateral trades to take place.

Actors at the grid edge gain the functionality previously reserved to owners of power station and system operators. They can choose who and when they trade energy with, either buying or selling. Having the technical possibilities to do so does not require them to take on this responsibility. In most cases it may be most attractive to delegate complex decision making to third parties or, in time, autonomous systems. The power over such choices gives end users greater self-determination over their energy use and the origin of their electricity. The degree to which they opt to take control along the dimensions in *figure 5* is at their discretion.

6.5.1 Opportunities in developing countries

The absence of a national grid infrastructure can in some ways be seen as an advantage for some underdeveloped regions. Instead of investing in large scale networks, smaller and more distributed solutions can be adopted first. The analogy to telephony illustrates the opportunity. Many developing countries never built an infrastructure of wired telephony. Instead, many regions 'leapfrogged' this step and embraced mobile networks from the start.

Similar developments are possible in energy. The first applications that are adopted when users gain access to electricity are not especially energy demanding. They include lighting and cellphone charging and the opening of barber shops with electric shavers. Refrigerators are adopted but often used very sparingly. In India it has been observed that some users turn fridges off overnight, because it is customary to finish fresh food by the end of the day. Subsequently there is no need to run the fridge continuously.

In the early stages these loads can be served with low power and low-voltage grids. The attractiveness of PV solar power combined with low diversification of loads makes flexibility an especially interesting challenge. The default option, which ought to be avoided for environmental and technology lock-in reasons, are backup diesel generators. Instead, intelligently operated storage and well managed demand can improve the utilization of available low-carbon resources.

As demand for power grows, so can local networks. Initial microgrids connecting neighboring houses can be interconnected, provided their operating principles are compatible. Such connected systems achieve better load and supply diversification and gain access to more sources of flexibility. It is an organic and efficient infrastructure development from the bottom up.

6.5.2 Replacing grids with data

A national grid serves two important functions. Firstly, it connects remote areas with large centralized power stations. Secondly, the scale of the network diversifies load profiles, making them smoother and reducing the ratio of peak to average load. Depending on the characteristics of loads, the reduction in peak generating capacity can be up to a factor of ten. This is to say that if each load center was to have its own flexible generator, the sum of all generators would need to be sized to ten times as much capacity as needed when connected to a common grid. With the emergence of smaller and more distributed generators, the need for the first function of the grid to connect remote sources is reduced. Local loads can be connected to local sources of supply with much smaller and subsequently lower voltage systems.

The second function, however, is becoming increasingly important. Not only does the greater volatility of local and less diversified loads need to be managed, but the sources themselves are more variable. This is where smart solutions will have significant impact. Data from all parts of the system will be required to improve forecasting on short and long time-scales. AI systems can detect when and where supply-demand mismatches are most likely to occur and even evaluate which mitigating measures are most socially acceptable or economically favorable.

As with autonomous vehicles, AI-driven autonomous energy systems will take decisions of ethical dimensions. Should the produce of a sensitive manufacturing process be prioritized over the thermal conditions in a local hospital? These decisions are currently taken by humans and often with unintended consequences. On August 9, 2019, a brief supply shortage in Great Britain was responded to with a supply disruption to the rail infrastructure. Although the power was restored in minutes, passengers were stranded for hours because the signaling hardware needed the be reset manually.

7 In summary

In summary, the Internet of things, data and intelligently connected systems have the ability not just to maintain energy service provision but to improve on personal choice and to give a sense of control and ownership. These solutions can identify inefficiencies in energy service provision and improve system planning and operation. Done right, such technologies can be a vital aspect of bringing wider society along on one of the greatest system transformations ever attempted.

Section 2:

Techno-economic implications of a net-zero transition

1 Introduction

If the impact of developments around the grid edge has huge societal implications, the same can be said for its impact on the markets, business and the business models and technologies they employ. This section examines the status of markets today and the opportunities that exist. It looks at the key technologies and the new business models at the grid edge. It looks at changing ownership and payment structures. It also explores an example business case to illustrate how all these elements come together at the grid edge to help bring about a transition to a net-zero energy system.

2 Market status and opportunities

To understand the opportunity and the speed at which a transition can be made to a net-zero energy system, it is important to understand the status of the market – both in size and conditions. The following considers these for end consumer markets, especially in Germany, but also looks at other international examples where applicable. It also examines end-consumer flexibility and efficiency potentials.

2.1 End consumer power markets addressing the grid edge

In Germany, the prices paid by end consumers may vary quite significantly depending on the consumer segment and the corresponding rules for the administratively determined elements of the price of power, such as taxes, levies, etc. On average, household consumers pay the most per kWh consumed, roughly €0.3 per kWh. However, for an assessment of (theoretical) market potentials and in order to calculate potential savings, volumes of power consumed must also be taken into account. Industrial consumers consume roughly half of Germany's overall power consumption. *Figure 1* combines these aspects and assesses theoretical market potentials by combining specific power prices and volumes consumed. A rough estimate shows that end-consumer power market volumes are approximately €100bn per year.

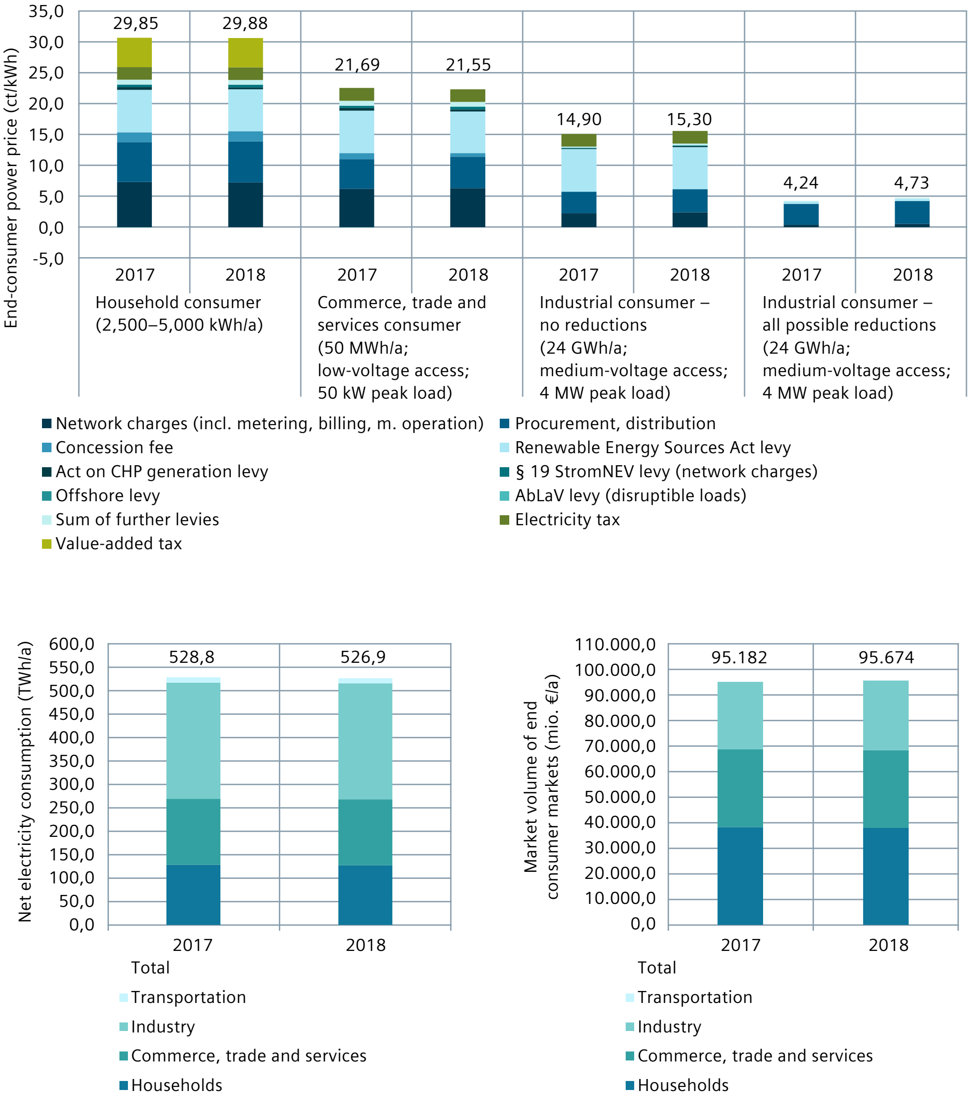


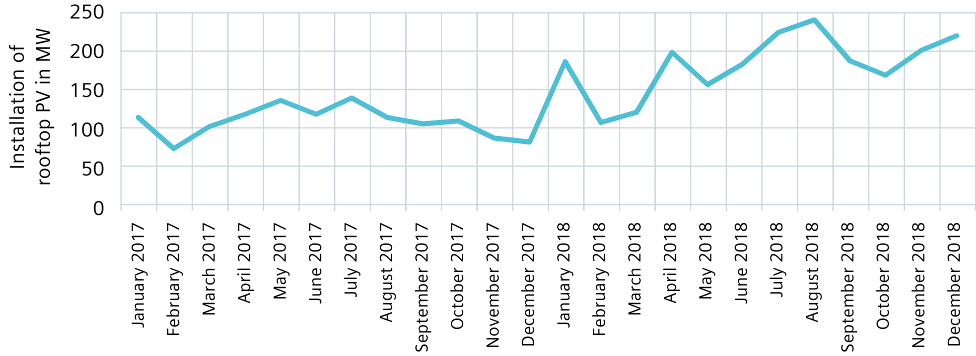
Figure 1:

End-consumer power prices, net electricity consumption per sector, and rough estimation of end-consumer market volumes (excluding transport sector).
Data Sources:
power prices[5,6]
taxes and levies[7]
net electricity consumption[8]
assumption for industrial electricity consumption with reduced charges (100 TWh/a) derived from[9]

The figures shown can, to some degree, be interpreted as the end consumers' willingness to pay for electricity from the power grid or a theoretical maximum estimate for the potential savings that can be shared between the consumer and a service provider. They do not, except to a limited extent, include the willingness to pay for additional services, such as the provision of 'green' energy, self-supplied or locally supplied energy and energy services (which may, for example, include flexible services or an assessment of energy saving potentials via energy consumption monitoring and feedback or via the cross-selling of energy-efficient appliances). To illustrate the growth in self-production and prosumer activity, the installation of rooftop photovoltaic power systems (rooftop PV) in 2017 and 2018 as a proxy for market volume growth is shown on the next page (*figure 2*). Due to a large decrease in costs for PV storage systems – roughly half the cost compared to 2013 – about every second rooftop PV plant is installed with a PV storage system[10].

Figure 2:

monthly new installations of rooftop PV in Germany from 2017–2018[11] .



From this analysis it can be concluded that, as far as market volumes and willingness to pay are concerned, household consumers as well as commerce, trade and services seem very attractive fields for setting up grid edge business models. Nevertheless, the technical infrastructure and its rollout costs as well as tariff design are crucial elements in their success.

2.2 Potentials and current political initiatives for energy efficiency and flexibility at the grid edge

Flexibility potentials describe the ability to elastically react to an external signal (such as price or a control signal) by changing power consumption[1]. A meta-analysis of energy efficiency and flexibility potentials of end consumers shows a broad range for these potentials, especially for household consumers. This is due to many methodical simplifications and assumptions that are necessary when assessing potentials for a broad range of end consumers. Whereas increases in energy efficiency can be achieved from almost every power device, one crucial element for assessing flexibility potentials is the question of which applications are eligible for load shifting – respectively load shedding controlled by a third party. There are high theoretical respective technical potentials, but it is very much uncertain to what extent control systems will be available and how much the end consumer will be prepared to accept load shifting and load shedding. In Germany, time-of-use tariffs or real-time-pricing are today only available to a very limited extent for smaller consumers, so incentives for load shifting and load shedding are widely lacking. In contrast, around the world, there are a lot of pilots and regimes for time-varying pricing, especially in the United States[12,13].

For flexibility, two main areas for usage can be distinguished: grid-motivated and market-motivated. As far as grid-motivated activation is concerned, it will likely be procured by network operators themselves, so eventually none or only few market opportunities for third parties may arise in this field besides some opportunities for aggregators, aggregating small (consumption) units.

1 "Flexibility potentials" in this section means the ability to elastically react to an external signal (price or control signal) by changing power consumption. Power output of prosumer plants is not considered here, but might be included as well.

Both energy efficiency and flexibility potentials are triggered by a smart meter infrastructure that enables the identification of potential savings in consumption patterns using close to real-time data feedback and tariff design. In Germany a potential drawback for small consumers is that the current smart meter rollout plan only includes end usages with a consumption of more than 6,000 kWh/a. This effectively means that many detached houses will either not be included, or will be included only on a voluntary basis after a cost-benefit analysis has been carried out[14]. In contrast, the rollout plan for Great Britain aims at installing 50 million smart meters for gas and electricity before 2050 and by December 2018 14.94 million had already been installed[15].

As far as commercial and industrial consumers are concerned, the metering infrastructure is often already available. Many energy-intensive industries have already used it to address what is a large cost factor – and as a result realized a big share of their overall energy-efficiency and flexibility potential. For smaller businesses and industries some unmet potential remains due to barriers such as a lack of financing opportunities, some information deficits, reservations about flexibility as far as product quality is concerned, current power market design, comparatively low earning potentials and a requirement for short payback periods or investment strategies putting the core business into the centre[16,17].

3 Key technologies at the grid edge

At the grid edge is a wide variety of technologies available that build an ecosystem of distributed energy capabilities, digital solutions and services[18]. Here we largely focus on those at the grid edge between the power sector and private households, but many of the technologies explored are equally applicable to other sectors.

The role of the consumer is key. As we move towards a net-zero energy system, the formerly passive consumer is evolving into a prosumer or even a 'prosumager'. The prosumer becomes more and more independent from traditional services by using distributed energy resources. The prosumager goes one step further by storing excess generated energy locally and only relying on the network sporadically to balance services and to ensure reliability. This system change can be accomplished using new technologies like blockchain and microgrids. Combining these technologies enables the prosumer to become independent of the traditional grid or even go off-grid[4].

The most relevant technologies can be broadly divided into four categories[19]: distributed energy generation, heating and cooling; distributed energy storage; flexible and controllable loads; measurement and control. However, across all these categories, there are many connections and synergies between these technologies.

Distributed energy generation, heating and cooling

Consumers may become prosumers by generating their own electricity using a small wind turbine, a small photovoltaic system, or by holding a share in a company that produces renewable energy locally and supplies the consumer[20]. This electricity can be used directly or it can be used in a second step for indirect electrified processes like Power-to-Heat or Power-to-Gas – a typical application being a heat pump. Another possibility is using cogeneration technology, which provides electricity and heat at the same time. Two common examples are cogeneration units using an internal combustion engine or a gas turbine, and fuel cells, which rely on an electrochemical process transforming the chemical energy into electricity while releasing heat. Electricity can also provide cooling – as used in air-conditioning systems.

Distributed energy storage

This category is strongly connected to the previous one. Here, the prosumager supplies energy to a local storage facility, enabling them to become more independent of the traditional grid. One option is direct short-term storage of electrical energy using a battery – widely available for households with a photovoltaic system[20]. With increasing ownership and use of electrical vehicles, these batteries can also be used for storage that provides control energy when needed. If electrical energy from renewable sources is not stored directly, heat or gas storage is a possible solution. In the case of heat storage, the electricity is used in a Power-to-Heat system to transform it into heat, which can be stored seasonally to enable the temporal decoupling of power generation and heat consumption. A reconversion of the stored heat to provide electrical energy is, as yet, not economically feasible. Another long-term solution is gas storage. The electrical energy can be stored in combination with a Power-to-Gas system, where the water electrolysis is used to generate hydrogen or methane, which can be stored and used directly. Alternatively, stored gas can be used as a fuel in a combustion power plant or in fuel cell applications to provide electrical energy[21].

Flexible and controllable load

Flexible and controllable load has several dimensions – including technological advancements like distributed generation, storage and automatic demand response – that play an important role in the transition to a net-zero energy system and provide the opportunities for new business models.

In the case of controllable load it is, for example, possible to include electric vehicles in a circuit, which will allow them to charge only in specific time slots only and this way benefit from lower electricity rate[20]. Another application of the concept is within smart buildings. Here, the equipment of a building is monitored and controlled by a building management system (BMS) that manages loads and enhances efficiency[22]. In order to implement this, the Internet of things (IoT) facilitates the complex intradevice communication and data flows that are required to operate these assets in a system-efficient manner.

Measurement and control

As stated earlier, the IoT is one of the most important ingredients of grid edge technologies. It enables the connection of physical and virtual objects as well as their collaboration through information and communication technology. The improvement of this technology over recent years has been substantial and this trend will continue through higher standardization and an extension of services. A BMS uses both the IoT and IP-networkFurther, which enables, for example, smart lighting to be controlled centrally and/or remotely to lower the energy consumption and to improve a consumer's experience. Further examples of the application of the IoT for measurement and control are within[22]:

Centralized chillers and boilers

Heat pumps

Various mechanical, electrical and plumbing systems within the building management system

Electrical systems for the energy distribution and storage

The sensors used to measure the relevant data for control and monitoring include demand-controlled ventilation, energy recovery ventilators, dedicated outdoor air systems, CO_2 sensors, and ultraviolet germicidal irradiation. In order to achieve as much energy efficiency as possible, a standardized all-inclusive BMS is used[22]. A large database and specific data analyse lead to a wide range of possible business models based on the BMS.

Microgrids are another important innovation at the grid edge. They offer the possibility of optimizing the consumption and distribution of local generation and storage. A microgrid can, for example, create a virtual power plant that aggregates the generation of several households in order to trade energy through peer-to-peer platforms[23]. This concept can only be realized when the microgrid communicates with a connected smart grid that manages distributed generation and storage as well as demand via centralized control using a distributed energy resource management system – so providing the operator with the necessary information about production and consumption[23].

In order to successfully implement a smart grid, smart meters are required – an innovation previously described. These provide the data used to control both energy demand and supply. By constantly monitoring the demand of customers, higher billing accuracy and grid reliability can be achieved. And as usage patterns become more transparent, customers are even enabled to respond to the market and to optimize their demand[24].

With an increasing share of fluctuating energy sources, the awareness of different supply costs at different times of the day becomes more important – allowing the consumer to respond to the current situation, for example by charging an electric car during hours where there is a higher supply than demand. Smart meters in combination with other developments, such as the IoT, therefore play a key role in providing more flexibility within energy demand throughout the day[23].

As the energy system transforms towards a more digitalized one, new business models are emerging to enable the realization of virtual power plants and distributed generation. One solution to enable transactions among and between consumers using existing infrastructure is through blockchain technology. This cryptographically secured distributed database system ensures the integrity of the transactions that are recorded within the blockchain without an intermediary. This is achieved by creating tamper-proof blocks within the blockchain that are linked to the preceding block. This system allows, for example, prosumers to trade their production directly between each other with so-called smart contracts. Thus, blockchain technology also provides more flexibility to the energy system – which is crucial for the success of a decentralized renewable energy system[25].

4 Business model framework applications

The transition towards a net-zero energy system triggered a change in value creation and related business models. At the grid edge, this is mainly driven by technological changes like the application of smart metering gateways[26]. Here, business model prototypes with a focus on consumers are becoming more significant – bringing new opportunities in the fields of energy or consumer services and platform-based solutions as well as in related analytics and measurement[19]. As the prosumer is a key element in a decentralized and bidirectional energy system[27], they therefore influence the landscape of these business models.

With the rising relevance of dispersed resources, possible business models at the grid edge have to be adapted to a decentralized energy world. Traditional companies like utilities and network operators and also market entrants like those from the information and communication sector are increasingly being challenged to offer service-oriented business models[28]. The design of these business models plays a crucial role in managing the complexity at the grid edge. A company that operates a business model at the grid edge is frequently described as an Energy Service Company (ESCO).

A typical concept is the offer of energy contracting where, as service providers, companies offer their customers the required form of energy (electricity, gas, heat, but also light, compressed air, etc.). These business models illustrate the possible link to sector coupling technologies, because service providers can, for example, easily add mobility concepts into their service package. Such customer-oriented energy services range from the use of analog measurement and control technology to digital components such as apps or platforms[29].

In general, digital platforms are one way of managing the large number of different users at the grid edge, as they serve to network different actors. They bring users and their technologies together in a new way or integrate actors who previously had no access to certain networks or markets. In this way, digital platforms promise to reduce transaction costs and generate additional value through network effects[30–32]. Based on these characteristics of platform-based business models, their function is described by the role of a market maker.

A digital platform offers – based on digitalization and related scale effects – the opportunity to make possible simple interaction between different actors in the energy industry. This aspect not only refers to the necessary software, but also to the integration of distributed metering and control technology. Given this aspect, platform-based business models at the grid edge are related to IoT technologies or IoT-platforms[33,34]. Further aspects are digital technologies such as blockchain to enable local energy markets[35].

Decentralized actors and their new concepts of market access, for example local energy trading platforms, enable peer-to-peer trading. A virtual power plant or virtual storage platform can be realized based on distributed small-scale energy production or storage in combination with smart meter technologies. One benefit comes from the use of local storage capacities or load shifting resources, as well as the excess production of prosumers this production is based on renewable energies, it can increase the contribution to emission reductions as a further value proposition[29].

The increasing complexity of local energy systems at the grid edge leads to the need for new service-oriented business models – and of particular importance are platform-based digital services. Their advantage is in the comparatively simple networking of various players as they act as market makers.

4.1 As-a-service business models vs. platform business models

With the growing importance of services for end users, service-oriented business models are becoming increasingly relevant. This becomes clear in the software area, where many products are provided in the form of 'software as a service'[36]. Furthermore, in the light of the increased use of cyber-physical systems at the grid edge, the complexity of the energy system is also increasing. Typical for the grid edge is the use of these systems to control and connect decentralized resources. These technical products are often combined with services when offered to the final customer. As such a service is often only made possible by the use of corresponding software, 'as a service' solutions are appropriate[37].

An 'energy as a service' concept is a solution for the local and decentralized energy systems at the grid edge. The main task is to ensure the technical operation of systems located at consumers' premises or sites and various generation and consumption technologies are applied in this context. Thus, ESCOs are not just service providers for the end customer – by coordinating different players to ensure the service for the end customer, they can also act as service provision orchestrators[29]. Due to this service orientation, it is possible to introduce sector coupling technologies, such as electric heating systems instead of fossil-fired boilers. If customer comfort is guaranteed, flexibility for the grid can also be provided by demand-side management concepts.

'As a service' business models offer customers advantages that go beyond the simple provision of technology or energy. By combining them with additional services, especially in the field of analytics, the ESCO can also cover a larger part of value creation. In addition, customers profit from the elimination of high initial investment requirements thanks to typically associated pay-per-use models. ESCOs can also address non-financially strong actors, such as households or non-commercial enterprises, as new customer groups[38]. The effects of CAPEX-intensity and the related aspects of risk allocation regarding the ownership model is discussed later.

Different platform-based business models are also relevant at the grid edge. Examples are not just platforms for energy services, but also peer-to-peer, virtual power plants or crowd-storage business models. These platforms are of advantage if the ownership of the assets is decentralized or the spatial distribution is crucial for the offered product. Examples from other industries are Airbnb for apartments or car sharing concepts, such as SHARE-NOW, in major cities. Such platforms are characterized by the fact that they do not own the decentralized technologies[31]. In the context of the grid edge, they do not possess their own physical infrastructure at the grid edge.

Energy services can be effectively offered through a platform-based approach. Companies use IoT-platforms to offer services like energy management, consumption optimization, consumption and consumer data analyses, and smart home solutions. In addition to market access, they offer services such as energy data management, meter reading, or the pure supply of electricity or final energy, such as heat. Further services can be offered by means of direct access to the customer – especially in the fields of energy efficiency or complete system solutions. Based on this access to the end customer, the offer of integrated mobility solutions or the use of flexibility for the energy system on the consumption side becomes possible. The latter can be realized by including technologies like heat pumps or EV batteries in the energy service package[29].

In companies with larger vehicle fleets, advantages over business models based on household customers become evident. The business-to-business model enables the realization of scale effects more efficiently and potential exists in nearly all companies with vehicle fleets. Commercial mobility management in combination with electromobility is also an aspect of an emission-free transportation sector[39]. The greater predictability and controllability of the loading processes also allows for the integration of additional services. One example is the offer of balancing energy and the possibility of further revenues based on improved predictability of static fleets.

4.2 Local energy platforms

With the increasing relevance of prosumers, the demand for (local) energy transfer or peer-to-peer transfer offers a new opportunity for business models. At this point, platform-based services provide the ability to organize more effectively individual consumption, renewable energy generation and, if present, storage. In addition to exchanges with neighbours, this also affects the optimization of local energy systems on-site and behind the meter[4].

The peer-to-peer platform business model provides a novel market platform for direct trading between customers. Based on artificial intelligence, transactions are processed on a peer-to-peer, blockchain or IoT-platform. An important aspect of this business model is the benefit created by eliminating intermediaries and therefore reduced transaction costs. The providers also make it possible to develop the necessary distributed local energy systems at the grid edge. Thus, peer-to-peer platforms are contributing to a transition towards net-zero emission. Potential revenue streams can be realized by fees for use of service but also by license fees or trading commissions[29].

Another interesting platform-based business model at the grid edge is a virtual power plant (VPP). These balance renewable fluctuations based on digitalization and stochastic analyses by covering a broad distributed generation portfolio and so can mirror the characteristics of a single conventional power plant[40]. A VPP acts as an aggregator by grouping various small power producers and selling their capacity within a virtual unit. Customers benefit from indirectly guaranteed entry to markets that are otherwise difficult to access, such as stock exchange trading. In contrast to this, peer-to-peer trading takes place directly between the owners of the distributed generation plants. The ESCO realizes income through service fees, commissions and flat rates as well as shared energy prices[29].

There are three key platform-based business models for local renewable energy systems – provenance platforms, community platforms and local-access platforms. Provenance platforms allow the direct exchange of local energy by giving the customers the chance to choose their preferred producer directly – and transparency is a key value proposition. Community platforms coordinate the energy flows by pooling, thus transferring part of the decision-making to the central energy management of the platform (an example is a VPP). In contrast to these two models, local access platforms do not use existing decentralized units. Based on a crowdfunding approach they enable investments in distributed resources like PV-plants on the basis a crowdfunding approach. The platform not only coordinates the financing, but also controls the allocation of generation to consumers (here also investors)[31].

One example of the realization of the provenance concept is the company[31] Enyway. This is a platform on which electricity producers and electricity consumers (mainly private consumers) can network. Enyway focuses on the region from where the electricity is demanded and produced – and the value proposition is cheap electricity from regional renewable sources. On the platform electricity sellers and buyers can get to know each other – so a direct buyer-seller connection[41] is made.

One prominent example of a community platform is the concept developed by Sonnen[31]. The basic concept is to integrate distributed storage fed by local small-scale PV generation in an intelligent manner. Local small-scale producers feed their surplus electricity into a virtual solar battery storage system and can withdraw the electricity if required. Smart meter technology is a central element within this business model – to obtain and manage the information about local production and consumption behind the meter. Furthermore, this information can be applied to sell the community's surplus energy on the wholesale market and so generate income for the ESCO and their local energy producers. Blockchain technology is applied to coordinate decentralized battery storage and to support grid stability by offering flexibility through an offer of balancing power[42].

It can be concluded that for local energy systems and the related business models the technologies at grid edge are crucial. The concepts are service-oriented and can address a broad group of users. In addition to the above-mentioned households and small businesses, the principles can also be applied to industrial applications. This applies primarily to the integration of renewable generation plants. For groups at the grid edge with larger connected loads, like industrial companies, the acceptance of flexibility concepts like load shifting and load shedding is the critical aspect. As described previously, the availability of appropriate control systems can contribute to the facilitation of new business models for industry.

Another positive aspect for business models at the grid edge in industry is the size of the connected loads. By integrating larger capacities into a platform, the offer of balancing energy can also address local and temporary grid congestion. Heat can also play an important role in industrial business models at the grid edge. Sector coupling technologies like power to heat in combination with thermal storages can also address the critical aspect of more flexible production processes. Related business models can offer heat as a service as well as balancing energy. In addition to the flexibility and integration of renewable energy, a further revenue stream is possible through generated heat that can be fed into a district heating network and generate a corresponding income.

5 Structures and perspectives on relevant business models

The cost structure of renewable energy technologies, as well as related devices, is characterized by CAPEX intensity compared to conventional technologies – which implies a higher risk for investment in grid edge technology. However, in contrast to conventional technologies, modern technologies can reduce OPEX as they do not need a fuel supply (e.g. PV and, to some extent, heat pumps) and can even be used in business models to generate income flows, thus, reducing cost of supply. This leads to several questions:

what investment structures do exist?

how could payment structures look?

5.1 Diversified ownership models to introduce flexibility and speed into the energy transition

Several different ownership models can be identified for grid edge technology. One critical element to differentiate between these models is the ownership of the (smart) meter as well as the (smart meter) gateway. In European countries, meter operation (and possession) is principally an unbundled (thus, explicit) market role[40]. However, as it was traditionally part of grid operation, in most situations, the meter will still belong to and be operated by the (distribution) grid operator. The ownership and operation of meters and gateways by end consumers is normally only seen in the industrial sector. This being said, the combination of meter operation and other grid edge technology is possible from a legal perspective (but might be questionable for a distribution grid operator).

Ownership structures for grid edge technologies (and thus the new business models) show more flexibility. The application of grid edge technology appears to be somehow similar to the deployment of technologies to reduce energy consumption and costs, for which often contracting solutions are found. Based on traditional contracting models[44], the following ownership (and operation) structures for grid edge technologies can be distinguished:

1. Performance model:
Ownership and operation of all grid edge technologies by an ESCO. ESCO is responsible for the provision of energy services.

2. System model:
Ownership of (parts or all) grid edge technology and supply of an explicitly defined (useful energy) supply by an ESCO (further conversion technologies, general application framework, etc. is still in the hands of the end consumer).

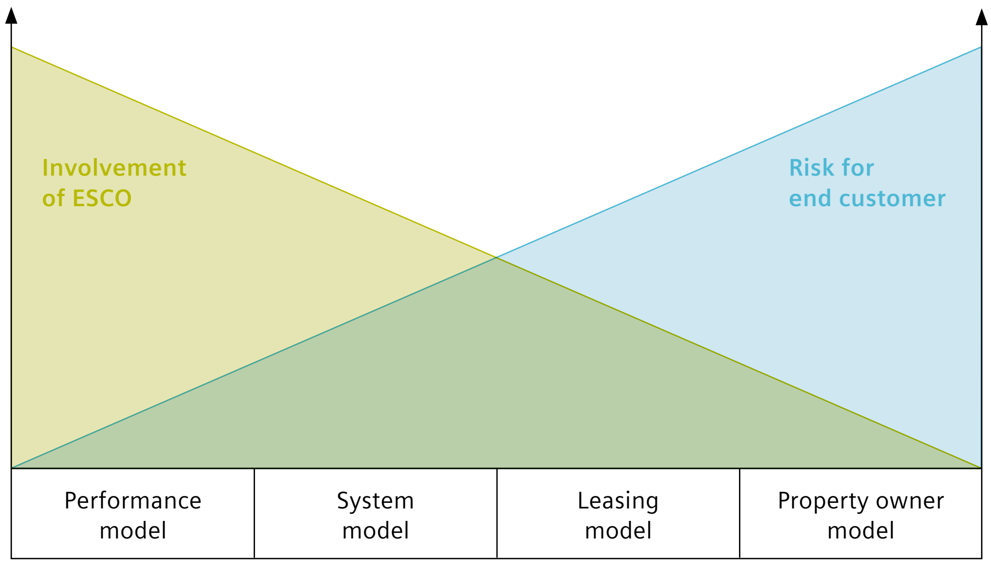
3. Leasing model:
The grid edge business company only supplies financing; the end consumer or a third party is responsible for operation.

4. Property owner model:
The end customer either owns and operates the technology or pays an ESCO to operate the system (and its components). However, no third party is directly involved in the financing process.

While the involvement of an ESCO decreases as we move from ownership structures one to four, the risk for the end customer increases. Furthermore, optimization potentials among grid edge technologies can be raised more easily by the ESCO in case one, while in case four the customer takes full responsibility and risks for the investment (see the next figure).

Figure 3:

Risk dependency in different ownership models.



The ownership (and operation) of the (smart) meter and gateway is not necessarily part of any of the models. Nevertheless, access to the consumption (and production) data is critical, especially for the performance model. Since the control of data access lies with the end customer, however, this can be safely guaranteed. For the optimization of grid edge technology it might be necessary to obtain highly granular data. Thus, one can argue, that the more comprehensive the ownership model is (especially model 1), the more likely the meter ownership (and operation) will be with the ESCO. The figure on the next page illustrates the differences of the various ownership options – of which several hybrid forms can occur.

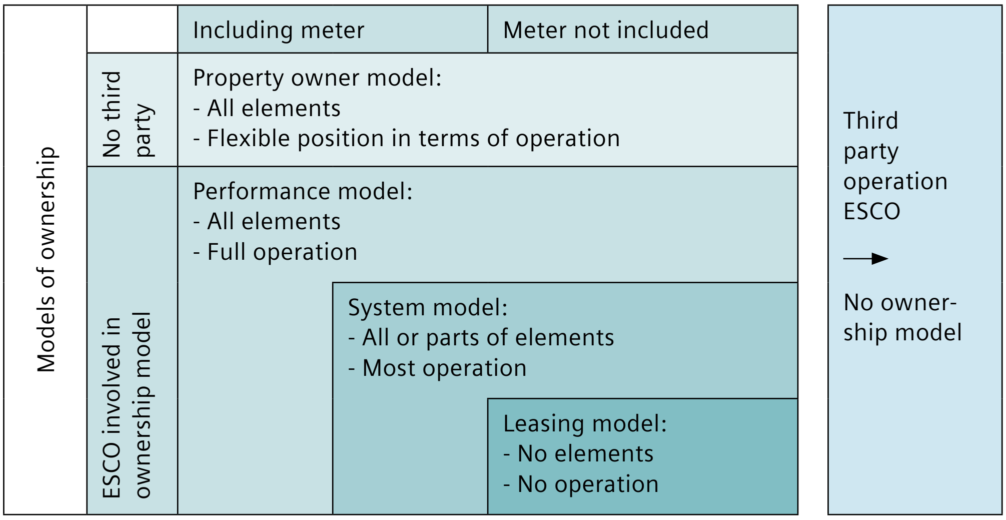


Figure 4:

Ownership models for grid edge technologies.

The more comprehensive a model, the more risks are borne by the ESCO. The performance model, for example, includes the ownership of several technological elements behind the grid edge, which might include the ownership of heat pumps or even electric vehicles for households, trade and service companies and (sometimes) industry (end) customers. The complexity of the system leads to full-service provision, which was historically more interesting for larger consumers, but might also become an opportunity for household customers. This development is supported by the increase in digitalization and automatization as well as economies of scale. At the same time, the performance model offers an ESCO the best economic opportunities as economies of scale for technical elements as well as system know-how can be applied.

The other extreme is a pure leasing model, where the ESCO focuses on financing and ownership of the technical elements remains with the ESCO (as long as there is no buyout by the end customer or prosumer). This leads to a situation where either a third party ESCO has to step in for operation or the customer needs to have well-developed know how. This might be interesting especially for industry customers not willing to take financial risks, but having potentially sufficient knowledge of energy services.

The system model is an interesting solution especially for the trade and services sector, being primary a B2B model. Some technical elements may be devolved to the ESCO, like heat or air conditioning for shops. However, the ESCO ownership doesn’t comprise production process-relevant aspects although useful energy might be supplied.

In summary, there are four basic ownership structures for grid edge business models and related technology elements. Furthermore, the possession of the meter introduces a second level to these four models. Data accessibility is crucial to all, meaning access to data must be given for any business model. Lastly, the risk for the customer decreases with the increase of the ESCO’s comprehensiveness, while the economic opportunities (and risks) increase for the ESCO.

5.2 Payment structures

The implementation of grid edge technologies leads to an increase in energy (especially electricity) related technologies behind the grid. For several technologies the investments are relatively high compared to conventional technologies. Examples are PV cells and battery storage for prosumers, which pay out over their lifetime, but require an initial investment that might be too high for a large proportion of possible end consumers. Furthermore, different ownership structures exist, not only for grid edge technologies or business models, but also for buildings and sites. While detached houses are predominantly owned by their inhabitants, apartments are often owned by real estate companies, at least in Germany, Austria and Switzerland[see 45]. In the trade and service sector, real estate or affiliated companies might own the building. This leads to a complex situation for ESCOs, where the ownership of the technical equipment as well as the ownership structure of the site defines the possible revenue streams and the different business model structures.

On the customer side, one has to distinguish between owners of an apartment, house or site (for industry as well as trade and services), leaseholders and tenants. Based on this, different types of contracts are possible. Furthermore, to overcome the possible occurrence of CAPEX problems, the ownership of the technological elements should not to be with the end user (as described in the section 'Diversified ownership models'). The different optional payment structures for business models at the grid edge are summarized in the table below.

Table 1:

Cross-matrix of ownership models and payment structures.

	Property owner model	Performance model	System model	Leasing model
Property	✓	✓	✓	✓
Leasehold	x	✓	✓	(✓)
Rent	x	✓	✓	x

As can be seen, not all ownership models can coexist with any ownership structure. However, the performance and the system model do always provide a solution to overcome the CAPEX restrictions.

For owners of sites, capital restrictions may be less of a problem, as these people already own a property. Being a homeowner leads to a general acceptance of the need for investment – which might decrease operational expenditures through good operational control of the technologies – and less interest in CAPEX-reducing options. For leaseholders the situation changes and, dependent on the contract might lead to restrictions that are similar to those for tenants. In these cases investments (and capital costs) become more problematic, as the interest on investments in grid edge technology is relatively low for these residents, due to short(er) residence periods. In addition, especially for tenants, the normal contracts do not provide for investment on the tenant side, but on the property owner's side. However, the benefits (as well as negative effects) of the installation of grid edge technologies will be on the tenant's side, not the property owner's. This creates a complex system, where first of all, the property owner has less incentive in investing in grid edge technologies as they do not benefit from their investment and the tenant might be interested in grid edge technology but is not the one to decide on the option (an investor-user-dilemma[46]). In this case, performance (and system) models can help as a facilitator. With low or no investment costs and a minimized risk at the customer side, the barrier for implementing grid edge technology is low for the property owner – and they can sell the technology advantages (e.g. cost reductions for heating, electrical car loading, etc.) to potential tenants. Last but not least, a performance model would even allow the tenant to participate in these new CAPEX-intensive business models. One example of such a construction is the German 'Mieterstrom' (tenant electricity) model, where tenants become prosumers by obtaining electricity from their own rooftops, which further increases acceptance of renewables[47].

6 Business case for owners and users of distributed energy sources and utilities

As described previously, the decarbonization of the energy system is directly linked to the distributed application of renewable generation. The IoT and related technologies like smart meter gateways or blockchain, as well as related data analytics tools, contribute to the fact that small consumers can also be actively involved in the system. As a result the variety of actors is rising, and a greater share of society becomes part of the energy transition. Thus, households or small-scale producers at the grid edge, who were previously not directly included in the system concepts, face the possibility of experiencing problems caused by the transition towards net-zero emissions.

As the volatility of generation rises due to higher shares of renewable-based electricity in the grid, distributed systems can contribute to maintaining network stability. In this context the ESCO also has the opportunity to increase the value of energy services for their customers. Additionally, by integrating small scale customers like households or commercial and trade into their business case, they offer new services to customers at the grid edge.

The example of a VPP can be used to illustrate a business model at the grid edge. Let us assume that a company wants to build a VPP consisting of prosumers with their own storage capacities and electric vehicles. The operator networks the decentralised battery storage facilities of its customers and sells the bundled power on the primary control market. As an incentive for customers and to reduce their initial investment, the platform operator pays the required smart metering gateway. Revenues would result from participating in this balancing of energy. However, the incorporation of this relevant technical infrastructure also offers further revenue opportunities – particularly those resulting from offering the whole concept in the form of white label solutions to utilities. In this case revenues would be generated from the sale of licenses for the VPP software and from more attractive long-term maintenance contracts[30].

This business model can be extended by a peer-to-peer (local) energy platform. This is possible because direct contact with the users at the grid edge already exists in form of the offered smart meters. Already networked prosumers (by the VPP) would benefit from the offer of a flat rate of electricity, which can be realized by the integration of multiple distributed storage units into a community storage. The individual prosumers share their renewable electricity with the other members of the VPP. Electricity trading within the community is only reflected on the balance sheet. The actual processing still takes place via the platform operator, who is also responsible for electricity procurement, balancing group management and billing. The members pay a monthly community fee and only the kilowatt hours consumed outside the free quantity of their flat rate electricity[30].

A further addition to this business model can come from the growing use of electromobility. The integration of the charging infrastructure as another consumption point at the grid edge offers customers the opportunity to increase their own consumption of electricity generated by the PV system. This is achieved by intelligently embedding the car batteries into the local energy system. Customer profits from fueling their car using their own green and free of charge electricity. This can also reduce the load on the power grid and increase grid stability. By linking the package with the peer-to-peer energy platform, this is also covers for situations where their own solar production does not cover consumption.

Section 3:

Conclusion: the key to net-zero energy

Conclusion

We are on the cusp of one of the most significant changes in our history. A transition towards an energy system that through greater control, efficiency and democracy will shape the way we live and the future of our planet. A fundamental change in the structure of our energy system – from centralized to decentralized and to net-zero carbon emissions. And it is at the grid edge where the innovations to drive this crucial change are happening.

Fundamental to this change is increased connectivity and the intelligent gathering and use of data. It harnesses the power of the IoT and ICT. It creates opportunities for local, distributed generation and storage to benefit all. It changes the role of the consumer – giving them more control, ownership and influence. It is supported by the development of new business models, new ownership and pricing structures.

The transition to this transformed system is already happening. There is a clear need, a market opportunity, and the political will. The technology, the strategies and the organizations are in place to support the change. Many changes are already taking place and the pace of change will only accelerate. From the grid edge a new net-zero energy system will emerge.

References Part 1

[1] Dodds, P.E., Staffell, I., Hawkes, A.D., Li, F., Grünewald, P., McDowall, W., Ekins, P., 2015. Hydrogen and fuel cell technologies for heating: A review. International Journal of Hydrogen Energy .

[2] Element Energy. Electric vehicle charging behaviour study. Final report, National Grid ESO, 2019. --> Page 10

[3] Fouquet, R., 2010. The slow search for solutions: Lessons from historical energy transitions by sector and service. Energy Policy 38, 6586–6596.

[4] Grünewald, P., McKenna, E. and Thomson, M. 2014. Keep it simple: time-of-use tariffs in high-wind scenarios. IET Renewable Power Generation, 9(2):176–183.

[5] Grünewald, P., 2013. Demand response for system balancing: Experience and future potential. European Demand Response and Dynamic Pricing Conference. 24–25 June .

[6] Grunewald, P., Diakonova, M., 2018. Flexibility, dynamism and diversity in energy supply and demand: A critical review. Energy Research & Social Science 38, 58 – 66. DOI: 10.1016/j.erss.2018.01.014.

[7] Grünewald, P., Torriti, J., 2013. Demand response from the nondomestic sector: early uk experiences and future opportunities. Energy Policy 61, 423–429.

[8] Heptonstall, P., Gross, R., Steiner, F., 2017. The costs and impacts of intermittency – 2016 update. Technology and Policy Assessment (TPA). UK Energy Research Centre.

[9] Jacobsen, H.K., Schröder, S.T., 2012. Curtailment of renewable generation: Economic optimality and incentives. Energy Policy 49, 663–675.

[10] Meckling, J., Nahm, J., 2019. The politics of technology bans: Industrial policy competition and green goals for the auto industry. Energy Policy 126, 470 – 479. DOI: 10.1016/j.enpol.2018.11.031.

[11] Sinden, G., 2007. Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand. Energy Policy 35, 112– 127.

[12] Sovacool, Benjamin K. 2009. "The Intermittency of Wind, Solar, and Renewable Electricity Generators: Technical Barrier or Rhetorical Excuse?" Utilities Policy 17 (3): 288–96. --> Page 7

[13] Strbac, G., Aunedi, M., Pudjianto, D., Djapic, P., Teng, F., Sturt, A., Jackravut, D., Sansom, R., Yufit, V., Brandon, N., 2012. Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future. Report for the Carbon Trust. Imperial College London

References Part 2

[1] Zibelman, A. How Distributed Energy Resources Are Disrupting the Utility Business Model. In Innovation and Disruption at the Grid's Edge; Elsevier, 2017; pp xxix–xxxiii. https://doi.org/10.1016/B978-0-12-811758-3.00028-0.

[2] Pollitt, M. G. Electricity Network Charging in the Presence of Distributed Energy Resources: Principles, Problems and Solutions. EEEP 2018, 7 (1). https://doi.org/10.5547/2160-5890.7.1.mpol.

[3] Koirala, B. P.; van Oost, E.; van der Windt, H. Community Energy Storage: A Responsible Innovation towards a Sustainable Energy System? Applied Energy 2018, 231, 570–585. https://doi.org/10.1016/j.apenergy.2018.09.163.

[4] P. Sioshansi, F. Innovation and Disruption at the Grid's Edge. In Innovation and Disruption at the Grid's Edge; Elsevier, 2017; pp 1–22. https://doi.org/10.1016/B978-0-12-811758-3.00001-2.

[5] BNetzA; BKartA (2019): Monitoringbericht 2017. Monitoringbericht gemäß § 63 Abs. 3 i. V. m. § 35 EnWGund § 48 Abs. 3 i. V. m. § 53 Abs. 3 GWB. as of 13. Dezember 2017.

[6] BNetzA; BKartA (2018): Monitoringbericht 2018. Monitoringbericht gemäß § 63 Abs. 3 i. V. m. § 35 EnWG und § 48 Abs. 3 i. V. m. § 53 Abs. 3 GWB. as of 21. November 2018.

[7] ÜNB (Transmission system operators for Germany); netztransparenz.de (2019): Details on levies and taxes on power in Germany. accessed Oct 28, 2019: https://www.netztransparenz.de/.

[8] BDEW(2019): Nettostromverbrauch nach Verbrauchergruppen. as of 03/2019. accessed Oct 28, 2019: http://www.bdew.de/service/daten-und-grafiken/nettostromverbrauch-nach-verbrauchergruppen/.

[9] BAFA (2019): Unternehmen bzw. Unternehmensteile, die im Jahr 2018 an den aufgelisteten Abnahmestellen von der besonderen Ausgleichsregelung profitieren. accessed Oct 28, 2019: https://www.bafa.de/DE/Energie/Besondere_Ausgleichsregelung/besondere_ausgleichsregelung_node.html.

[10] BSW (2019): Statistische Zahlen der deutschen Solarstrombranche (Photovoltaik). accessed Oct 28, 2019: https://www.solarwirtschaft.de/fileadmin/user_upload/bsw_faktenblatt_pv_2019_3.pdf.

[11] BNetzA; Bundesnetzagentur (2019): Veröffentlichung von EEG-Registerdaten. PV-Anlagen (außer PV-Freiflächenanlagen). Datenmeldungen vom 1. Januar 2017 bis 31. Januar 2019. accessed Oct 28, 2019: https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEG_Registerdaten/EEG_Registerdaten_node.html.

[12] Faruqui, A.; Hledik, R.; Palmer, J. (2010): Time-varying and dynamic rate design.

[13] Faruqui, A.; Sergici, S. (2010): Household response to dynamic pricing of electricity: a survey of 15 experiments. J Regul Econ (pp. 193–225). accessed Nov 8, 2019: https://doi.org/10.1007/s11149-010-9127-y.

[14] Messstellenbetriebsgesetz - MsbG (2016): Gesetz über den Messstellenbetrieb und die Datenkommunikation in intelligenten Energienetzen. accessed Nov 8, 2019: http://www.gesetze-im-internet.de/messbg/MsbG.pdf

[15] Department for Business, Energy & Industrial Strategy (UK) (2019): Smart Meter Statistics. Quarterly Report to end December 2018. Experimental National Statistics. accessed Nov 8, 2019: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/789632/2018_Q4_Smart_Meters_Report_FINAL.pdf

[16] Gege, M.; Heib, M. (2013): Erfolgsfaktor Energieeffizienz: Investitionen, die sich lohnen; wie Unternehmen und öffentliche Einrichtungen Energie und Kosten einsparen können, 2. Auflage. oekom-Verlag. München.

[17] Langrock, T.; Achner, S.; Jungbluth, C.; Marambio, C.; Michels, A.; Weinhard, P.; Baumgart, B.; Otto, A. (2015): Potentiale regelbarer Lasten in einem Energieversorgungssystem mit wachsendem Anteil erneuerbarer Energien.

[18] Patwardhan, Y. (2018): Power Systems of the Future. Grid Edge Technologies.

[19] Giehl, J. F.; Göcke, H.; Grosse, B.; Kochems, J.; Müller-Kirchenbauer, J. (2019): Vollaufnahme und Klassifikation von Geschäftsmodellen der Energiewende. Zenodo. accessed Nov 8, 2019: https://doi.org/10.5281/zenodo.2620264.

[20] Orton, F.; Nelson, T.; Pierce, M.; Chappel, T. (2017): Access Rights and Consumer Protections in a Distributed Energy System. In Innovation and Disruption at the Grid's Edge; Academic Press (pp 261–285). accessed Nov 8, 2019: https://doi.org/10.1016/B978-0-12-811758-3.00014-0.

[21] Sterner, M.; Stadler, I. (2014): Energiespeicher – Bedarf, Technologien, Integration. Springer Berlin Heidelberg. accessed Nov 8, 2019: https://doi.org/10.1007/978-3-642-37380-0.

[22] Minoli, D.; Sohraby, K.; Occhiogrosso, B. (2017): IoT Considerations, Requirements, and Architectures for Smart Buildings – Energy Optimization and Next Generation Building Management Systems. IEEE Internet Things J. accessed Nov 8, 2019: https://doi.org/10.1109/JIOT.2017.2647881.

[23] Knieps, G. (2017): Internet of Things and the Economics of Microgrids. In Innovation and Disruption at the Grid's Edge. Academic Press (pp 241–258). accessed Nov 8, 2019: https://doi.org/10.1016/B978-0-12-811758-3.00013-9.

[24] Baak, J. (2017): Bringing DER Into the Mainstream: Regulations, Innovation, and Disruption on the Grid's Edge. In Innovation and Disruption at the Grid's Edge; Academic Press (pp 167–186). accessed Nov 8, 2019: https://doi.org/10.1016/B978-0-12-811758-3.00009-7.

[25] Löbbe, S.; Hackbarth, A. (2017): The Transformation of the German Electricity Sector and the Emergence of New Business Models in Distributed Energy Systems. In Innovation and Disruption at the Grid's Edge. Academic Press (pp 287–318). accessed Nov 8, 2019: https://doi.org/10.1016/B978-0-12-811758-3.00015-2.

[26] Eisenhardt, K.; Graebner, M. (2007): Theory Building from Cases: Opportunities and Challenges. Academy of Management Journal (pp 25–32). accessed Nov 8,2019: https://doi.org/10.5465/AMJ.2007.24160888.

[27] Kästel, P.; Gilroy-Scott, B. (2015): Economics of Pooling Small Local Electricity Prosumers – LCOE & Self-Consumption. Renewable and Sustainable Energy Reviews (pp 718–729). accessed Nov 8, 2019: https://doi.org/10.1016/j.rser.2015.06.057.

[28] Webb, J.; Wilson, C. (2017): Powering the Driverless Electric Car of the Future. In Innovation and Disruption at the Grid's Edge. Academic Press (pp 101–122). accessed Nov 8, 2019: https://doi.org/10.1016/B978-0-12-811758-3.00006-1.

[29] Giehl, J. F.; Göcke, H.; Grosse, B.; Kochems, J.; v. Miculicz-Radecki, F.; Müller-Kirchenbauer, J. (2019): Data Documentation: Vollaufnahme und Klassifikation von Geschäftsmodellen der Energiewende. Zenodo. accessed Nov 8, 2019: https://doi.org/10.5281/zenodo.3518997.

[30] Germanus, N. (2018): Entwicklung eines Bewertungsmodells für plattformbasierte Geschäftsmodelle in der Energiewirtschaft, Masterarbeit, Technische Universität Berlin, Fachgebiet Energie- Und Ressourcen-management.

[31] Kloppenburg, S.; Boekelo, M. (2019): Digital platforms and the future of energy provisioning: Promises and perils for the next phase of the energy transition. Energy Research & Social Science (pp 68–73). accessed Nov 8, 2019: https://doi.org/10.1016/j.erss.2018.10.016.

[32] von Engelhardt, S.; Wangler, L.; Wischmann, S. (2017): Eigenschaften und Erfolgsfaktoren digitaler Plattformen, Eine Studie im Rahmen der Begleitforschung des Technologieprogramms AUTONOMIK für Industrie 4.0 des Bundesministeriums für Wirtschaft und Energie.

[33] Krylovskiy, A.; Jahn, M.; Patti, E. (2015): Designing a Smart City Internet of Things Platform with Microservice Architecture. In 2015 3rd International Conference on Future Internet of Things and Cloud. IEEE (pp 25–30). accessed Nov 8, 2019: https://doi.org/10.1109/FiCloud.2015.55.

[34] Spano, E.; Niccolini, L.; Pascoli, S. D.; Iannaccone, G. (2015): Last-Meter Smart Grid Embedded in an Internet-of-Things Platform. IEEE Transactions on Smart Grid (pp 468–476). accessed Nov 8, 2019: https://doi.org/10.1109/TSG.2014.2342796.

[35] Mengelkamp, E.; Notheisen, B.; Beer, C.; Dauer, D.; Weinhardt, C. (2018): A blockchain-based smart grid: towards sustainable local energy markets. Computer Science – Research and Development (pp 207–214). accessed Nov 8, 2019: https://doi.org/10.1007/s00450-017-0360-9.

[36] Benlian, A.; Hess, T. (2011): Opportunities and risks of software-as-a-service: Findings from a survey of IT executives. Decision Support Systems (pp 232–246). accessed Nov 8, 2019: https://doi.org/10.1016/j.dss.2011.07.007.

[37] Al Faruque, M. A.; Vatanparvar, K. (2016): Energy Management-as-a-Service Over Fog Computing Platform. IEEE Internet Things Journal. (pp 161–169). accessed Nov 8, 2019: https://doi.org/10.1109/JIOT.2015.2471260.

[38] Waters, B.(2005): Software as a service: A look at the customer benefits. Journal of Digital Asset Management (pp 32–39). accessed Nov 8, 2019: https://doi.org/10.1057/palgrave.dam.3640007.

[39] Öko-Institut (2016): Gewerbliche Elektromobilität für Alle - Zwischenergebnisse und Handlungsempfehlungen aus dem Projekt "ePowered Fleets Hamburg".

[40] Pandžić, H.; Morales, J. M.; Conejo, A. J.; Kuzle, I.(2013): Offering model for a virtual power plant based on stochastic programming. Applied Energy (pp 282–292). accessed Nov 8, 2019: https://doi.org/10.1016/j.apenergy.2012.12.077.

[41] enyway (2019): Our Purpose. accessed Nov 8, 2019: https://en.enyway.com/about/

[42] Sonnen Group (2019): What Is the SonnenCommunity?. accessed Nov 8, 2019: https://sonnengroup.com/sonnencommunity/

[43] European Parliament and the Council of the European union (2019): Directive (EU) 2019/944 (2019).

[44] DIN (2013): DIN 8930-5:2003-11.

[45] Eurostat (2019): Wohneigentumsquoten in ausgewählten europäischen Ländern im Jahr 2017. In Statista. accessed Nov 6, 2019: https://de.statista.com/statistik/daten/studie/155734/umfrage/wohneigentumsquoten-in-europa/.

[46] Ekardt, F.; Heitmann, C. (2009): Energetische Sanierung im Altbestand und das EEWärmeG: Kann das Investor-Nutzer-Dilemma ökologisch-sozial aufgelöst werden. In Recht der Energiewirtschaft.

[47] Behr, I., Großklos, M. (2017): Praxishandbuch Mieterstrom: Fakten, Argumente und Strategien. Springer Vieweg.

Smart Infrastructure intelligently connects energy systems, buildings and industries to adapt and evolve the way we live and work.

We work together with customers and partners to create an ecosystem that intuitively responds to the needs of people and helps customers to better use resources.

It helps our customers to thrive, communities to progress and supports sustainable development.

Creating environments that care.
siemens.com/smart-infrastructure

Published by
Siemens Switzerland Ltd

Smart Infrastructure
Global Headquarters
Theilerstrasse 1a
6300 Zug
Switzerland
Tel +41 58 724 24 24

University of Oxford
Centre for the Environment
South Parks Road
Oxford OX1 3QY
UK

Technische Universität Berlin
Fachgebiet Energie- und
Ressourcenmanagement
Fraunhoferstr. 33–36
10587 Berlin
Germany