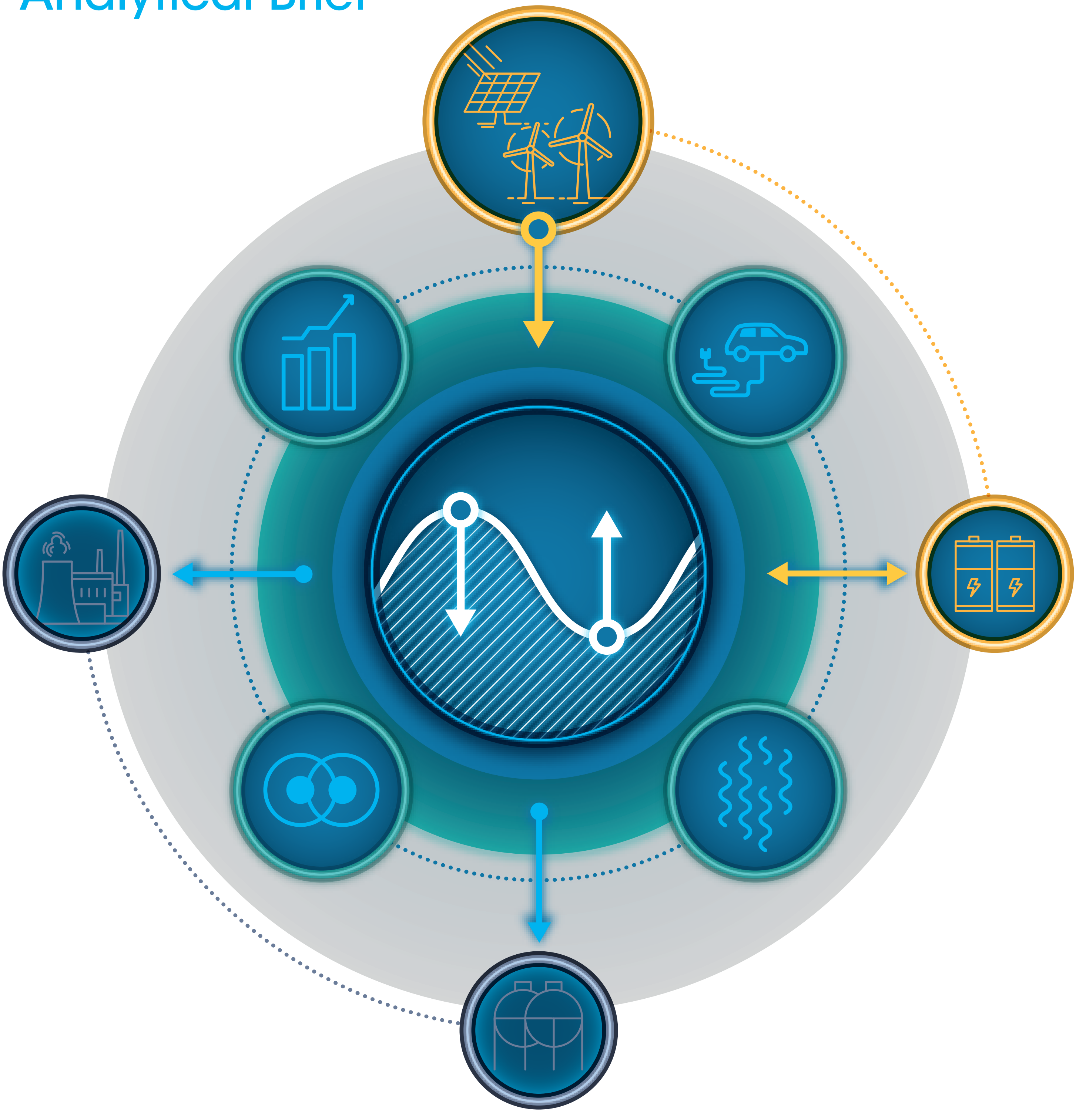
IRENA
International Renewable Energy Agency

DEMAND-SIDE FLEXIBILITY FOR POWER SECTOR TRANSFORMATION

Analytical Brief



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ISBN 978-92-9260-159-1

Citation: IRENA (2019), *Demand-side flexibility for power sector transformation,* International Renewable Energy Agency, Abu Dhabi.

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

ACKNOWLEDGEMENTS

This analytical brief benefited from input and review of experts: Marko Aunedi (Imperial College London); Julia Matevosyan (ERCOT); George Giannakidis (ETSAP); Alban Joyeau, Cristina Gómez Simon and Mathilde Lallemand (ENTSO-E); Alastair Martin (Flexitricity); Arina Anisie, Julien Marquant, Laura Gutiérrez, Lorenzo Sani, Luis Janeiro, Paul Komor, Raul Miranda and Sean Collins (IRENA).

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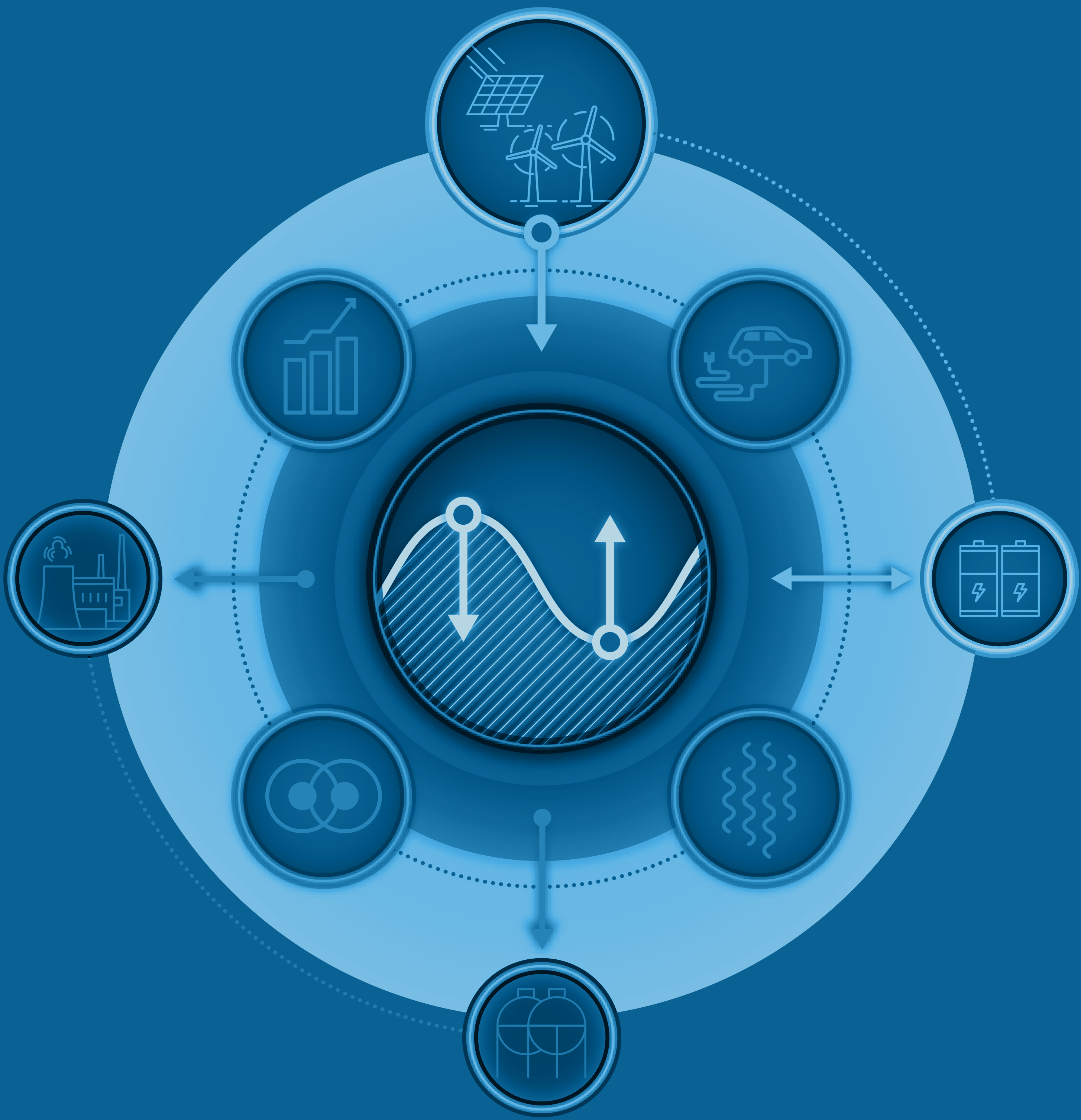
ABBREVIATIONS

°C	degrees Celsius
aFRR	automatic frequency restoration reserve
CAISO	California Independent System Operator
CHP	combined heat and power
COP	coefficient of performance
DVGW	German Association for Gas and Water
EDF	Électricité de France
EJ	exajoule
EV	electric vehicle
ERCOT	Electricity Reliability Council of Texas
FCR	frequency containment reserve
FFR	fast frequency response
FRR	frequency restoration reserve
GW	gigawatt
Hz	Hertz
ICT	information and communications technology
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LaaR	loads acting as a resource
MW	megawatt
PV	photovoltaic
RRS	responsive reserve service
TWh	terawatt-hour
UFR	under frequency relay
UK	United Kingdom
US	United States
V1G	unidirectional vehicle charging
V2B	vehicle-to-building
V2G	vehicle-to-grid
V2H	vehicle-to-home
V2X	vehicle-to-everything
VRE	variable renewable energy

EXECUTIVE SUMMARY



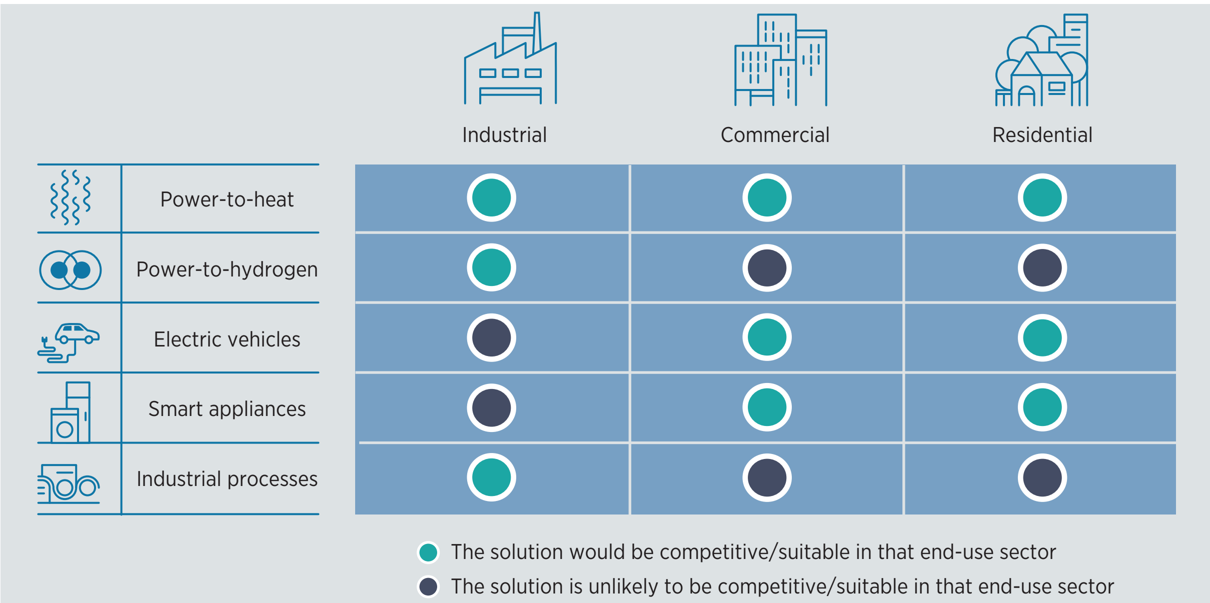
Decarbonisation of the energy sector comes with a set of challenges. The energy transition is linked to increasing penetration of variable renewable energy (VRE) together with an increase in the electrification of end-use sectors, both of which are key for long-term decarbonisation and the achievement of climate goals. If not well-planned, however, large shares of VRE together with the rapid expansion of electrification could affect the reliability of the power system. In this context, an increase in flexibility is necessary to mitigate potential mismatches in supply and demand induced by these changes. Flexibility must be harnessed not only on the supply side but also on the demand side, an approach that is referred to as demand-side flexibility.

Demand-side flexibility can be defined as a portion of the demand, including that coming from the electrification of other energy sectors (*i.e.*, heat or transport via sector coupling), that could be reduced, increased or shifted in a specific period of time to: 1) facilitate the integration of VRE by reshaping load profiles to match VRE generation, 2) reduce peak load and seasonality and 3) reduce electricity generation costs by shifting load from periods with high price of supply to periods with lower prices.

Different sources of demand-side flexibility can be combined to form innovative solutions. These include sector coupling (power-to-heat, power-to-gas and smart charging of electric vehicles) together with smart appliances in residential and commercial buildings and industrial demand response. These solutions can have different suitability depending on the end-use sector analysed (industrial, commercial or residential).

Today, a variety of real use cases for demand-side flexibility can be found. The present analytical brief maps out six different use cases for demand-side flexibility based on different solutions and end-use sectors. These cases involve different maturity levels and different timescale impacts, with illustrative examples provided for each of them. One illustrative example is industrial demand response providing reserves, as done in the US market by the Electric Reliability Council of Texas (ERCOT).

Demand-side flexibility is already a reality and is being unlocked in some parts of the world. However, there is still a long way to reach the full potential of this flexibility source: according to the International Energy Agency, the potential , expressed as the sum of flexible loads at each hour of the year, is 4 000 terawatt-hours (TWh) (on average 457 GW) today and expected to be 7 000 TWh (on average 800 GW) by 2040. To fully unlock this potential, a toolbox of different innovations is necessary for the successful implementation of each demand-side flexibility solution in different end-use sectors.



Note: Competitiveness/suitability is based on how inexpensive the solution is in comparison to others for the same sector. For example, the industrial sector has very few renewable options apart from green hydrogen, whereas direct electrification with renewables is a cheaper alternative for the commercial and residential sectors. Therefore, the potential for gaining demand-side flexibility from hydrogen production could be larger in industry.

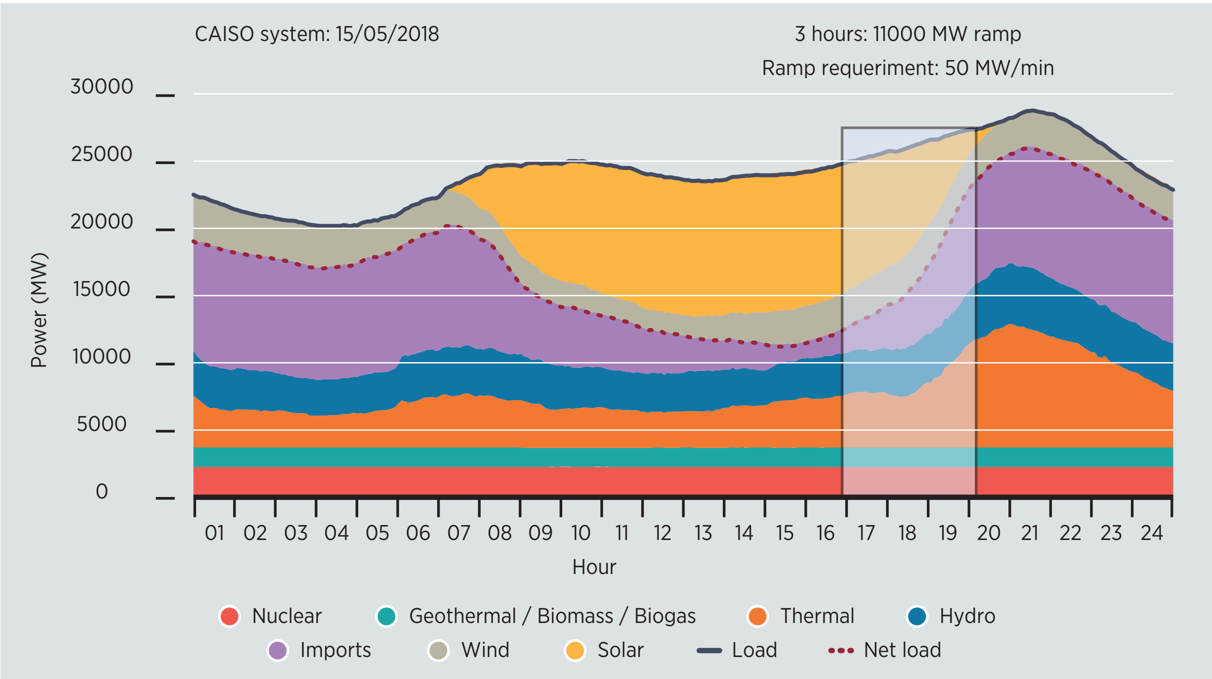
1. INTRODUCTION

The energy sector needs to experience a deep transformation worldwide and to achieve full decarbonisation. This is one of the main outcomes of the Paris Agreement, adopted in December 2015, in which parties agreed to take the appropriate measures to limit the increase in global temperature to less than 2 degrees Celsius (°C), with efforts to limit it to less than 1.5°C. This implies a complete decarbonisation of the energy sector. To achieve this, renewable energy has been identified as one of the key solutions. To meet the goals of the Paris Agreement, the share of renewable energy in global annual electricity generation will need to increase from 25% today to 86% in 2050 (IRENA, 2019a).

From this 86%, around 70% will come from variable renewable energy (VRE) sources[1], accounting for 60% of global annual electricity generation (IRENA, 2019a). Decarbonisation, however, comes with some challenges that must be overcome to achieve these sustainability goals.

First, a high penetration of VRE sources, which are characterised by variability and uncertainty, poses a challenge to the power sector across different time scales, from the short to the long term. An example widely used in the literature is the "duck curve" that first appeared in California. The duck curve occurs in power systems with a high penetration of solar photovoltaics (PV), which results in very high net load[2] ramping requirements given that the sun only shines during the day and not at night (CAISO, 2016). An example of the duck curve in the California Independent System Operator (CAISO) system is shown in Figure 1.

Figure 1 Net load curve for the California power system for 15 May 2018, when high solar PV penetration resulted in the duck curve



Source: CAISO, 2019. Figure based on Mashal and Sloane, 2018.

1 Variable renewable energy sources are wind, solar PV, run-of-river hydropower and concentrating solar power without thermal storage. However, the term VRE is commonly used to refer to wind and solar PV.

2 The net load is the electricity demand minus generation from VRE.

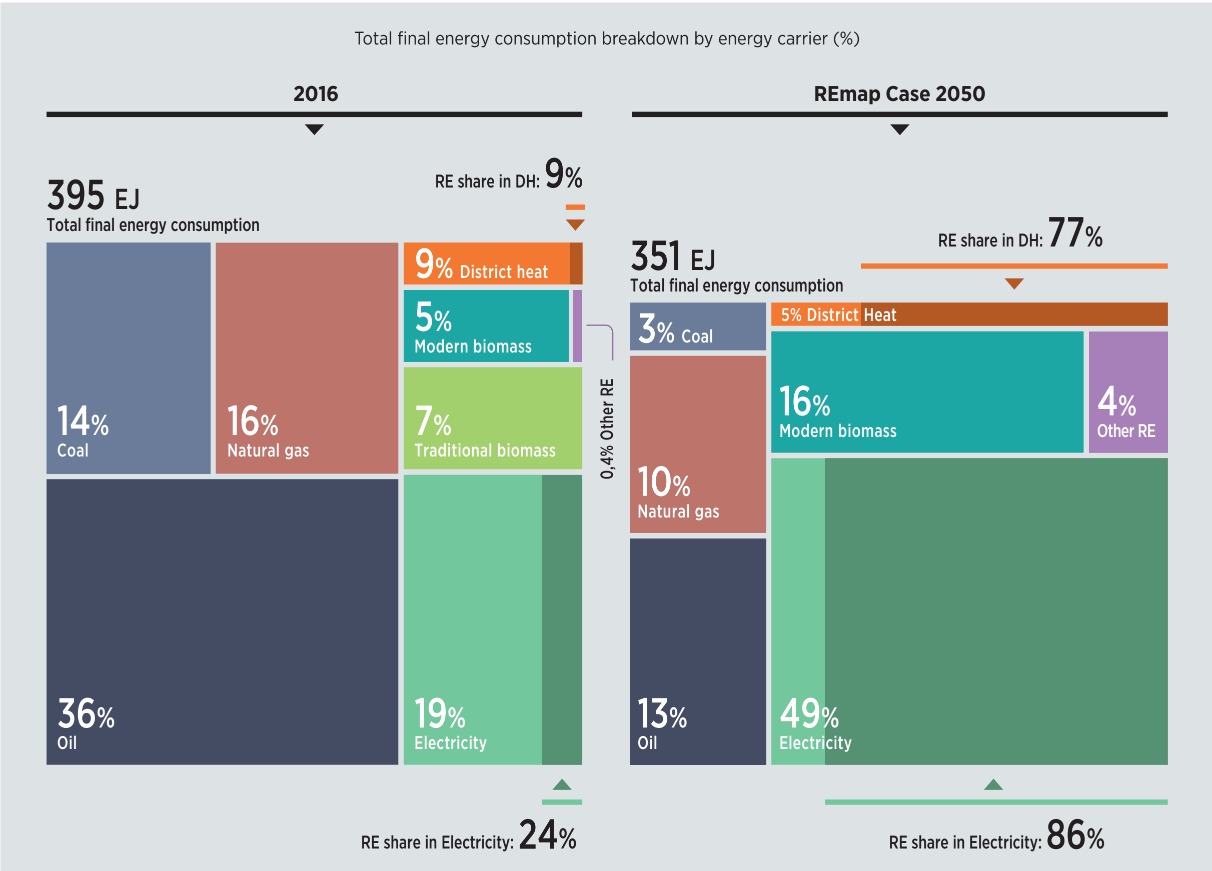
The second challenge is increasing electrification of end-use sectors, namely buildings, industry and transport. Electrification of end-use sectors is seen as a key solution to decarbonisation given the efficiency gain achieved by electrifying these sectors. Electrification, according to the REmap decarbonisation scenario of the International Renewable Energy Agency (IRENA), is expected to increase the share of electricity in final energy consumption for all energy applications from 20% today to 49% in 2050 (IRENA, 2019a).

Electrification goes in parallel with decarbonising the power sector, generating 86% of power from renewable sources. In absolute terms, this implies an increase in electricity consumption from 79 exajoules (EJ) (21 944 terawatt hours, TWh) today (out of 395 EJ or 109 722 TWh of total final energy consumption) to 172 EJ (47 778 TWh) in 2050 (out of 351 EJ or 97 500 TWh of total final energy consumption), with 148 EJ generated from renewable energy sources, which translates to 41 111 TWh (see Figure 2).

Electrification can have a direct impact on power system adequacy and reliability if not planned accordingly. On the one hand, electrification could greatly increase power demand, creating challenges in covering the peak and increasing ramping requirements. On the other hand, it could reshape demand profiles, creating the need for innovations in demand forecasting techniques and analysis, in order to determine the practicality of aligning the evolution of the demand profile given increased electrification with an increasingly variable generation mix.

These two challenges call for a single word: flexibility. IRENA defines flexibility as "the capability of a power system to cope with the variability and uncertainty that solar and wind energy introduce at different time scales, from the very short to the long term, minimising curtailment of power from these variable renewable energy (VRE) sources and reliably supplying all customer energy demand" (IRENA, 2018a).

Figure 2 Breakdown of total final energy consumption by energy carrier in 2016 and REmap Case 2050 (EJ)



Source: IRENA, 2019a

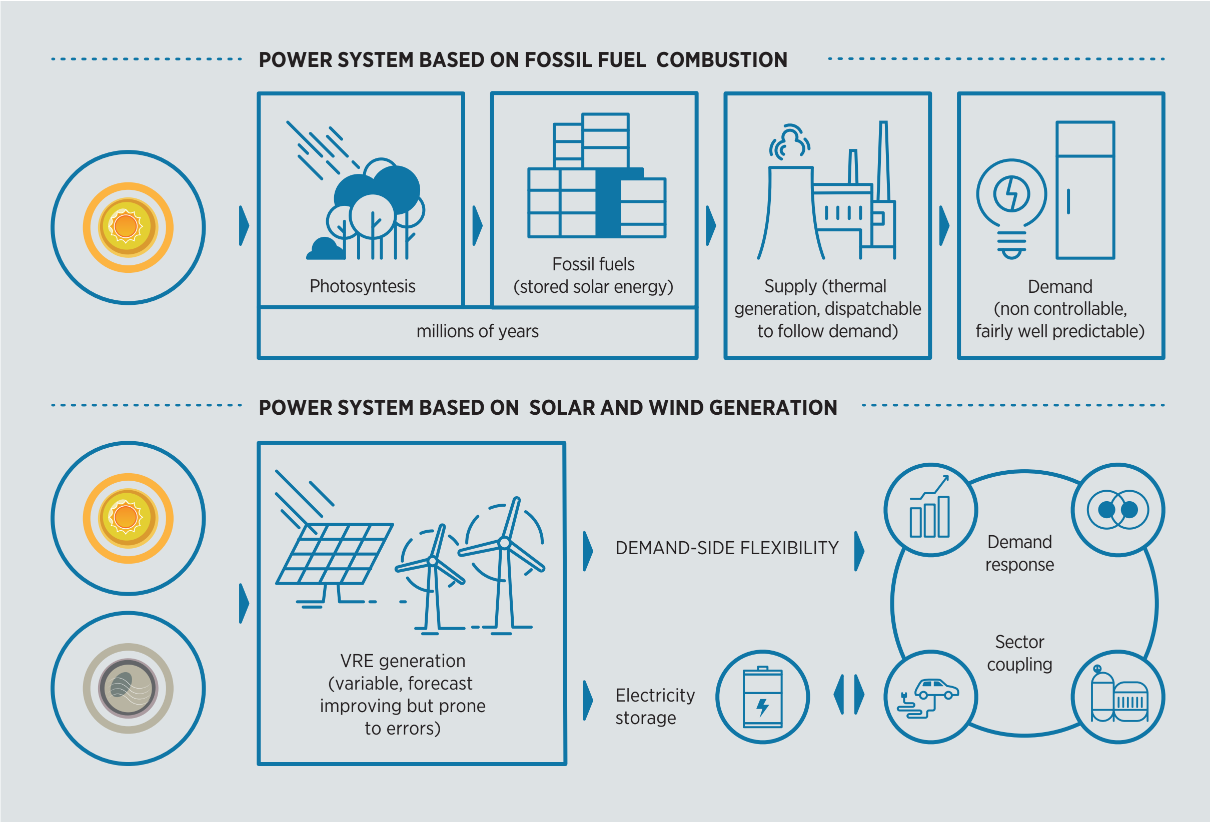
Flexibility has been typically harnessed on the supply side (for example, using thermal flexible power plants). With the increasingly urgent requirement to decarbonise energy use, however, the need has arisen worldwide to look more closely at **demand-side flexibility**.[3]

This also entails embracing electrification as an important part of the global energy transformation. Electrified demand can be considered as a flexible resource that can support grid integration of VRE, provided that it is observable and controllable. Figure 3 shows that in the past years, the energy supply was controllable, and demand did not need to be flexible. However, as the share of VRE increases today, supply becomes less and less controllable and demand needs to become a flexible resource, in order to increase power system reliability and facilitate the energy transition.

Demand-side flexibility can be defined as a part of the demand, including that coming from the electrification of other energy sectors (*i.e.,* heat or transport via sector coupling[4]), that could be reduced, increased or shifted in a specific period of time to: 1) facilitate integration of VRE by reshaping load profiles to match VRE generation, 2) reduce peak load and seasonality and 3) reduce production costs by shifting the load from periods with high price of supply to periods with lower prices.

The concept of controlling demand, however, is not new. For example, New Zealand's system operator has been controlling demand since the 1950s with the introduction of hot water ripple control that allows the distribution companies to switch off customers' electric water heaters if required (Transpower, 2019). Another example is the load shedding schemes that many European countries have had in place

Figure 3 Power system structure before and today with the different roles of demand



3 There are five key technical options to increase system flexibility: supply-side flexibility (e.g., new flexible power plants), demand-side flexibility (e.g., sector coupling), flexibility from storage (e.g., batteries), grid infrastructure (e.g., transmission expansion) and improved operation (e.g., more efficient hydro-thermal co-optimisation).

4 Note that electrification and sector coupling are not equivalents. Sector coupling will take place only if the electrified resources are used in a way that favours VRE integration.

for decades and that encourage large consumers, mostly industries, to shed load if the system requires it[5]. The Spanish interruptibility service (REE, 2019) and the German interruptible loads (TenneT, 2019a) are examples of this approach[6]. In Europe, demand response programmes have been minimal due to many barriers, such as the absence of the right price signals or of a regulatory framework that allowed business models to flourish (although this has been changing in the last few years, as shown in this brief).

In the United States (US), interruptibility services have been in place since the early 1970s, and since the early 2000s many independent system operators have implemented demand response programmes (for example, the Electric Reliability Council of Texas (ERCOT) industrial demand response participation in the ancillary services markets or the New York Independent System Operator (NYISO) Day Ahead Demand Response Programme), which are closer to the concept of demand-side flexibility. What is new under demand-side flexibility, and what this brief presents, is the possible inclusion of sector coupling with the electrification of heat, hydrogen production and transport, and a higher level of sophistication of residential demand thanks to advanced telecommunications and information and communications technology (ICT) infrastructure such as smart meters. Demand can therefore be an active participant in all end-use sectors provided that the right technology and incentives are in place.

Estimating the potential of demand-side flexibility in different end-use sectors is a complex task that requires deep quantitative analysis; however, some global, regional and national estimates of this potential[7] can be found in the literature.

For example, the International Energy Agency (IEA) estimates that the current operational demand-side flexibility of 40 GW could grow to 200 GW in 2040, while current potential of 4000 TWh (457 GW average), expressed as the sum of flexible loads at each hour of the year, is expected to grow to 7000 TWh (800 GW average) by 2040. Due to the increasing penetration of electric vehicles (EVs) and the electrification of heat in buildings (IEA, 2018).

On a regional level, the Directorate-General for Energy (2016) shows that the theoretical potential for 2010 in the European Union is 95.7 GW (around one-sixth of the demand peak) and would evolve to 120.8 GW in 2020 and 160.9 GW in 2030 due to the development in energy consumption of heat pumps and EVs. Finally, on a national basis, countries such as France, Germany and the US have done several analyses of the demand response potential.

This analytical brief provides an overview of demand-side flexibility at present and how it is expected to evolve in the future. Section 2 summarises existing solutions that can provide demand-side flexibility and classifies them by end-use sector, mapping the most suitable solutions per sector. Section 3 presents six examples of demand-side flexibility in actual practice, while Section 4 presents key innovations to enable these six examples (see also Box 1 for background). Finally, Section 5 provides some recommendations for policy makers on how best to utilise demand-side flexibility in the creation of a sustainable, reliable power system based on renewables.

5 This has been a controversial topic and some authors see interruptible load schemes as hidden subsidies for heavy industry, ince they are not being used anymore (Ecofys, 2014).

6 Note that both examples are services where demand signs a contract with the system operator in order to be shed if needed (i.e., demand participates voluntarily). In some countries demand is involuntarily shed because of reliability issues. In this case, this is not demand-side flexibility but would be considered as loss of load and thus a flexibility issue of the system.

7 Note that this is theoretical potential, which includes all facilities and devices of the consumers suitable for demand response. The next step is to calculate technical potential, which includes only devices that can be controlled because they have the infrastructure to do so, as well as the economic potential, which is the part of the technical potential that can be operated in a cost-efficient way.

Box 1 Background to this analytical brief: IRENA's *Innovation Landscape* study

A recent study, *Innovation Landscape for a renewable-powered future* (IRENA, 2019b), maps and categorises the many examples of innovation and innovative solutions emerging to support the integration of variable renewable power. The report aims to provide decision makers with a clear, easily navigable guide to the diversity of innovations currently under development, or in some cases already in use, in different settings across the globe.

The *Innovation Landscape* overview is based on the analysis of hundreds of innovative projects and initiatives being implemented around the globe. The analysis identifies 30 key innovations that are supporting VRE integration, emerging across four dimensions of the power sector: enabling technologies, business models, market design and system operations (see Section 4 of this brief, where some of these innovations are described in relation to the concept of demand-side flexibility).

However, these innovations do not emerge in isolation. On the ground, implemented solutions for the integration of VRE come from the synergies of different innovations across the different dimensions. This is called systemic innovation. The Innovation Landscape highlights 11 emerging solutions that illustrate the bringing together of several innovations in a complementary way. These solutions unlock flexibility across the whole power system: supply side, demand side, and the grid, and some other factors can unlock system-wide flexibility.

The following are related to demand-side flexibility:

- Solution VI: Distributed energy resources providing services to the grid
- **Solution VII: Demand-side management**
- Solution VIII: Renewable energy mini-grids providing services to the main grid
- Solution IX: Optimising distribution system operation with distributed energy resources.

This analytical brief builds on the IRENA Innovation Landscape report as well as the IRENA report *Power system flexibility for the energy transition* (IRENA, 2018a), which presents the different sources of power system flexibility available in the energy sector and summarises key elements of demand-side flexibility for power sector transformation.

Source: IRENA, 2019b

2. SOLUTIONS TO PROVIDE DEMAND-SIDE FLEXIBILITY

Demand-side flexibility can be provided only by a set of technologies that, given their characteristics, are suitable to be controllable and can be found in the industrial, commercial and residential sectors. In this analytical brief five solutions, each including different technologies, are identified. These are: power-to-heat, power-to-hydrogen, battery electric vehicles, domestic appliances and industrial demand response. This section provides an overview of each solution and maps its competitiveness or suitability in each sector (see Figure 4).

Demand-side flexibility can only be provided by controllable technologies

2.1 Power-to-heat

Coupling the heat and power sectors is also referred to as power-to-heat. The electrification of heat can increase peak demand and ramping requirements (for instance, when during a cold period all heating devices turn on at the same time) and impose additional reliability requirements on a system that was not well planned. However, if the coupling of sectors is done in a smart way, the electrification of heat (via power-to-heat) can contribute to VRE integration and decarbonisation (Bloess *et al.*, 2017).

To achieve this, heat demand should be met with devices such as heat pumps or electric boilers that could also be combined with thermal storage to provide additional flexibility (for example, a system composed of a heat pump and thermal storage could absorb the excess VRE in a specific period, store it in the thermal storage and use it at a later stage to cover heat demand when VRE generation is low or electricity prices are high).

Figure 4 Demand-side flexibility technology mapping by end-use sector

	Industrial	Commercial	Residential
Power-to-heat	Competitive/suitable	Competitive/suitable	Competitive/suitable
Power-to-hydrogen	Competitive/suitable	Unlikely	Unlikely
Electric vehicles	Unlikely	Competitive/suitable	Competitive/suitable
Smart appliances	Unlikely	Competitive/suitable	Competitive/suitable
Industrial processes	Competitive/suitable	Unlikely	Unlikely

● The solution would be competitive/suitable in that end-use sector

● The solution is unlikely to be competitive/suitable in that end-use sector

Note: Competitiveness/suitability is based on how inexpensive the solution is in comparison to others for the same sector. For example, the industrial sector has very few renewable options apart from green hydrogen, whereas direct electrification with renewables is a cheaper alternative for the commercial and residential sectors. Therefore, the potential for gaining demand-side flexibility from hydrogen production could be larger in industry.

- **Heat pumps** are devices that move heat from low-temperature sources to high-temperature heat sinks by using a compressor that consumes electricity. Heat pumps are characterised by being highly efficient devices (one unit of electricity can produce 4 to 5 units of useful heat[8]). Additionally, some heat pumps can be controlled, in the sense that their output can be variable. However, although their costs are falling, their capital costs are still high. Heat pumps are typically used to supply space heating and cooling for residential, commercial and industrial uses (IRENA and IEA ETSAP, 2013) and are a viable option to displace fossil fuels (in particular natural gas) from the heat supply and to advance the decarbonisation of heat, provided that the power sector is also being decarbonised. While today there are 20 million heat pumps worldwide, this number is expected to grow to 334 million by 2050, according to the REmap global energy transformation scenario (IRENA, 2019a).
- **Electric boilers or electric water heaters** are devices that use electricity to heat water. In these devices, electricity flows through the heating elements, which due to their high ohmic resistance produce heat according to Joule's law[9]. Their efficiency is much lower than that of heat pumps (typically 1 unit of electricity produces 1 unit of heat) but higher than conventional fossil-fuelled boilers. The capital costs of these devices are much lower and therefore they are increasingly common today.
- **Thermal storage** is a type of energy storage with capacity that absorbs and releases heat (or cold), when needed. Thermal storage helps to balance the supply and demand for heating or cooling more efficiently. There are several technology types with their own characteristics, which are covered in detail in IRENA's *Innovation outlook: Thermal energy storage* (IRENA, forthcoming-a) These can be divided into sensible, latent, thermochemical heat storage and mechanical-thermal coupled systems.

Power-to-heat can be decentralised, meaning that each consumer owns a heating device (for example, heat pumps, electric boilers or direct heating), or it can be centralised, where heat is supplied to customers through district heating networks. District heating is a way to supply residential and commercial buildings and industrial users with heat for space heating, hot water and process heat through a heat distribution network, capable of storing significant heat energy (IEA ETSAP, 2013). Combined heat and power[10] (CHP) plants, electric boilers and centralised heat pumps are in this case some of the most relevant technologies for heat generation.

Power-to-heat solutions could be competitive/suitable in the industrial, commercial and residential sectors:

8 This depends greatly on the technology and temperature difference at which a heat pump operates. A coefficient of performance (COP) of 4 to 5 is achievable for ground-source heat pumps, but for air-source heat pumps it is more likely to be around 3 on normal days and can fall below 2 on very cold days.

9 Joule's law states that the heating power generated by a conductor is proportional to its resistance multiplied by the square of the current flowing through it.

10 Note that CHP may be a source of flexibility or inflexibility depending on how decoupled the power and heat generation are.

- **Power-to-heat in industry:** According to Nowak (2018) industry uses 2 388 TWh of yearly final energy consumption for heating and cooling purposes in Europe alone, most of it for process heat. Some of this energy can be provided by heat pumps depending on the temperature level required. For instance, in Taibi *et al.* (2012) heat pumps are seen as suitable for low-temperature applications, such as processes in the food and beverage sector (for example, refrigeration processes). For high-temperature processes, electric boilers would be more suitable. Both electric boilers and heat pumps could unlock a large amount of demand-side flexibility in the industrial sector, especially if combined with thermal storage. District heating can also cover the heat demand for industrial demand response.
- **Power-to-heat in commercial buildings:** Because buildings require heating and cooling systems to maintain comfortable space temperatures, large-scale heat pumps possibly coupled with thermal storage could provide this service to the commercial sector while at the same time providing demand-side flexibility to the system by generating and storing heat when electricity prices are low to use it at a later stage. District heating can also provide heat to this sector.
- **Power-to-heat in the residential sector:** This can be provided with heat pumps or electric boilers and may also include thermal energy storage. The presence of thermal energy storage (for example, a hot water boiler) greatly increases the flexibility that can be provided to the system. District heating can also supply heat to this sector.

2.2 Power-to-hydrogen

Within the concept of power-to-gas – which is the process of converting electricity into a gas fuel such as hydrogen or methane – power-to-hydrogen is the process of converting electricity into hydrogen.

Hydrogen is an energy carrier, like electricity, that is raising interest across different countries and institutions worldwide. Hydrogen can be used in parallel with electricity to absorb the energy contained in sun and wind and reach consumers that otherwise would not be reachable.

In IRENA (2018b), hydrogen produced with renewable power is identified as the potential missing link of the energy transition that could help to deeply decarbonise the industrial, commercial and residential sectors. Today the amount of hydrogen produced with renewable power is very low (only 4% of hydrogen production, mainly as a by-product), but it is expected to rise to 3 EJ by 2030 and to 19 EJ by 2050, accounting for more than half of the hydrogen demand (29 EJ) that year, according to the REmap global energy transformation scenario (IRENA, 2019a).

This production of hydrogen from renewable power is achieved via electrolysers by coupling the hydrogen and power sectors, also referred to as power-to-hydrogen. Electrolysers are devices that use electricity to split water intro hydrogen and oxygen. Electrolysers can provide demand-side flexibility by adjusting hydrogen production to follow wind and solar power generation profiles in periods of high resource availability (and thus, low electricity prices) and can also provide grid balancing services.

Additionally, hydrogen can be injected and stored in the natural gas network (with some upgrades[11]) or in dedicated hydrogen storage facilities over the long term, making it possible to store the excess VRE generation by effectively providing seasonal storage. For more on renewable power-to-hydrogen see IRENA (2018b) and IRENA (2019c).

Power-to-hydrogen could be suitable mainly in the industrial sector:

- **Power-to-hydrogen in industry:** Hydrogen is used in several industry sectors and applications such as refineries, ammonia production and the chemical industry (IRENA, 2018b). If this hydrogen is produced from renewable electricity (typically when renewable energy penetration is high and prices are below a certain threshold), the electrolysers could be used to provide demand-side flexibility by following the variations in VRE profiles. Depending on the technology used, they can also be qualified to provide grid services and therefore earn revenues from the services market.

2.3 Electric vehicles

The third sector coupling alternative is facilitated through the electrification of transport with electric vehicles. The number of EVs in the world today is around 6 million but is expected to increase to 1 166 million by 2050, according to the REmap global energy transformation scenario (IRENA, 2019a). EVs can have different charging strategies. The simplest one is usually referred to as uncontrolled charging and means that EVs will charge at maximum power as soon as they are plugged into the grid. This charging strategy is not flexible and can pose a challenge to the power system if the number of connected EVs is high, increasing peak load and ramping requirements and posing additional flexibility issues to the system.

This issue can be tackled by adopting smart charging strategies. IRENA (2019d) defines smart charging as a way of optimising the charging process according to distribution and/or transmission grid constraints, local availability of renewable energy sources and customers' preferences.

11 This is already being done by the German Association for Gas and Water (DVGW), which currently allows admixtures of 10% hydrogen in the existing gas network. Additionally, DVGW is developing a regulatory framework where the target will be a 20% hydrogen feed (FuelCellsWork, 2019).

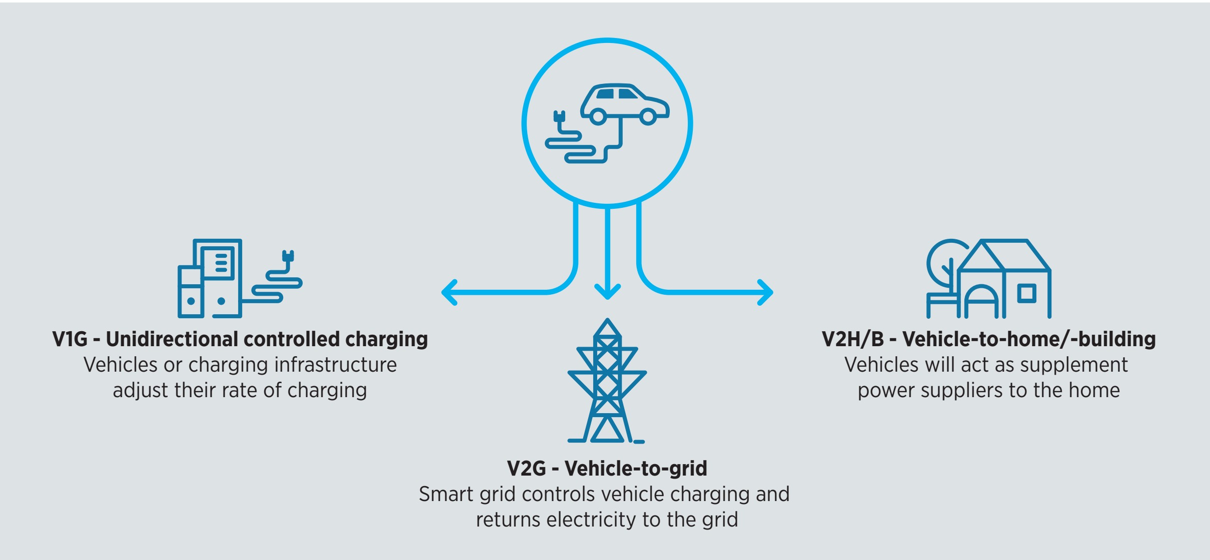
When charged smartly, EVs can provide demand-side flexibility by charging when prices are low, therefore following VRE availability and avoiding charging during scarcity events when prices are very high, causing, among other things, less stress in the distribution and transmission grid. The two main types of smart charging strategies are unidirectional control (also called V1G) and bidirectional control (vehicle-to-everything, V2X), which can be subdivided into vehicle-to-home (V2H) and vehicle-to-grid (V2G). Figure 5 shows the different smart charging strategies.

- **EV charging in commercial buildings and public places:** Because this charging usually occurs during the day, if smart infrastructure is in place the EVs could help integrate a higher amount of solar PV generation in the system, reducing carbon dioxide emissions and total production costs by providing demand-side flexibility (Taibi *et al*., 2018).
- **EV charging at residential houses:** In this case, the EVs are usually connected in the late afternoon or early evening once consumers come back from work, and then charged during the night. If no smart infrastructure is in place and charging is uncontrolled, this could pose a reliability issue to the system. If smart infrastructure is in place, EVs could help integrate a higher amount of VRE, mainly wind, by providing demand-side flexibility that could come by shifting load from high-price periods to low-price periods or by providing reserves (Taibi *et al*., 2018).

2.4 Smart appliances

Some appliances, either domestic or commercial, can also be used to provide demand-side flexibility if the right ICT infrastructure (for example, smart meters, sensors, communications technology, the Internet of Things, etc.) is in place. The most relevant types of appliances identified in the literature as potential providers of demand-side flexibility include[12] electric dryers, washing machines, dishwashers, fridges and freezers (Baucknecht *et al*., 2016; Scholz *et al*., 2014). The use of these smart appliances depends on the consumer's behaviour (*i.e.*, the consumer will use the dishwasher when needing to wash dishes) and therefore the idea behind this type of demand-side flexibility is that the consumer will react to price signals and use these appliances during low-price periods.

Figure 5 Forms of smart charging of electric vehicles



Source: IRENA (2019d)

12 Residential heat pumps, such as the ones used for air conditioning, are considered as a power-to-heat solution and therefore are excluded from smart appliances.

Smart appliances could add a significant volume of demand-side flexibility to the system; however, they have restrictions associated with availability and consumer behaviour. For instance, for most appliances, consumers can shift their load to other periods but only for a limited time (for example, if the consumer does not use the washing machine now, she or he will still need to use it later in the day), so their availability for load shifting is restricted (Bilton *et al.*, 2014).

Smart appliances as a source of demand-side flexibility could be suitable in the commercial and residential sectors:

- **Commercial smart appliances:** These appliances typically require higher electricity volumes and therefore can be a relevant source of demand-side flexibility (especially via an aggregator that provides different services to the grid – see Box 2 – but also responding to price signals). Commercial smart appliances could be, for example, the refrigeration systems (fridges and freezers) of a supermarket.
- **Residential smart appliances:** Smart appliances in the residential sector could also provide demand-side flexibility (for example, via an aggregator that provides different services to the grid – see Box 2 – or responding to price signals) if the proper infrastructure (*i.e.*, smart meters) is in place. Examples of domestic smart appliances could be washing machines, dryers or fridges.

2.5 Industrial demand response

As shown in the next section, industrial consumers can have solutions such as power-to-heat and power-to-hydrogen as part of their demand-side flexibility potential; however, industries also have other processes that require electricity, and these could also provide some demand flexibility by shifting load if required. Examples of these processes include cement production, electric arc furnaces for steel production, electric ovens, aluminium production, wood pulp production and paper manufacturing (Bauknecht *et al.*, 2016).

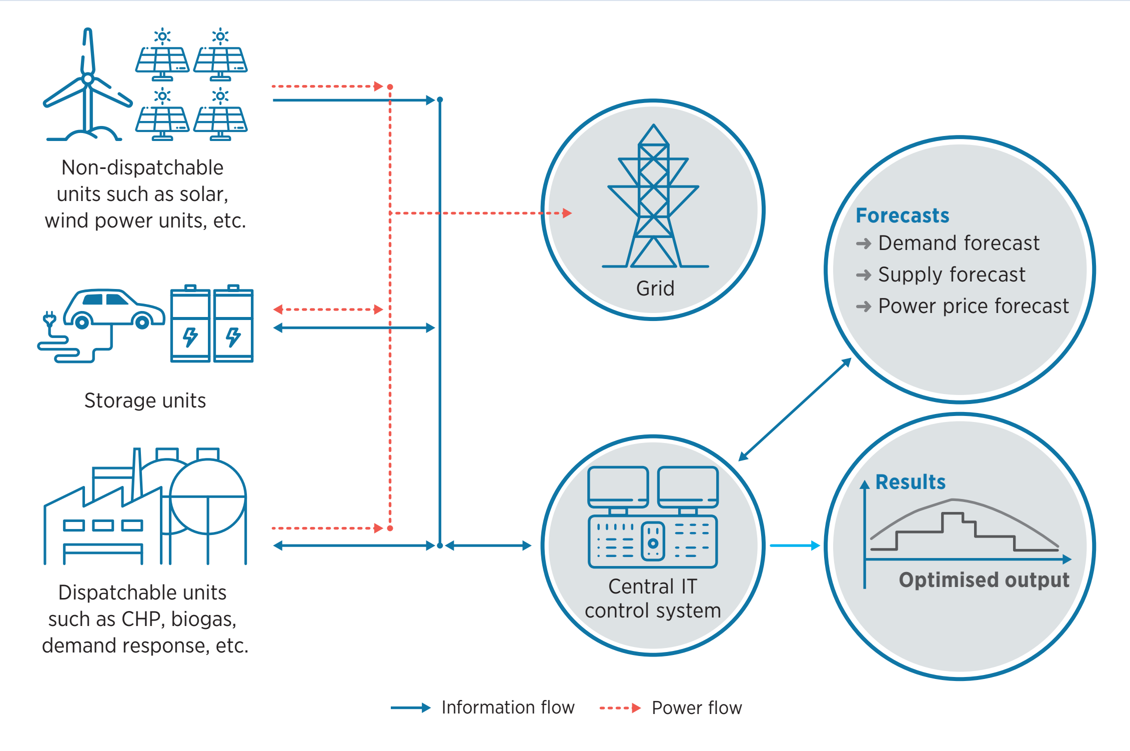
Industrial processes as a source of demand-side flexibility are only suitable/competitive in the industrial sector:

- **Industrial demand response:** Processes that require a high supply of electricity such as wood pulp production or paper manufacturing could be managed to provide demand-side flexibility by shifting the load required for these processes.

Box 2 How aggregators enable demand-side flexibility

An aggregator is a **grouping of agents** in the power system (*i.e.*, consumers, producers, prosumers or any mix thereof) to act as a single entity when engaging in power system markets (both wholesale and retail) or selling services to the operator (Burger *et al.*, 2016). IRENA, in its innovation brief on aggregators, refers to this new market participant as a company that operates a virtual power plant, which is an aggregation of disperse distributed energy resources with the aim of enabling these small energy sources to provide services to the grid (IRENA, 2019e). Figure 6 shows a schematic representation of an aggregator:

Figure 6 Overview of an aggregator



Note: A central IT control system or a decentralised energy management system (DEMS) sends an optimised schedule to the dispatchable distributed energy resources.
Source: IRENA, 2019e

An aggregator can use distributed energy resources from all end-use sectors, from industrial to residential. Its key benefit is **allowing customers to participate** in different markets by providing **local flexibility, load shifting, and services to the grid** and the electricity system as a whole.

The role of aggregators can be vital to enable demand-side flexibility, especially from the residential sector since residential customers are typically small actors whose priority is to have a reliable and cheap service with the least possible effort. Aggregators would allow the participation of these customers in different services with no need for the consumer to monitor markets continuously. However, to exploit the full potential of demand-side flexibility and other distributed energy resources, aggregators would have several requirements:

1) a regulatory framework that enables them to participate in the market,
2) advanced metering infrastructure (AMI) such as smart meters, broadband communication infrastructure, network remote control and automation systems and large amounts of real-time data and
3) advanced forecasting tools and techniques to optimise the scheduling of distributed energy resources (for example, by better predicting the VRE profiles and load, demand-side variations in the net load can be better observed and scheduling of distributed energy resources can be improved).

For more information on aggregators see IRENA (2019e).

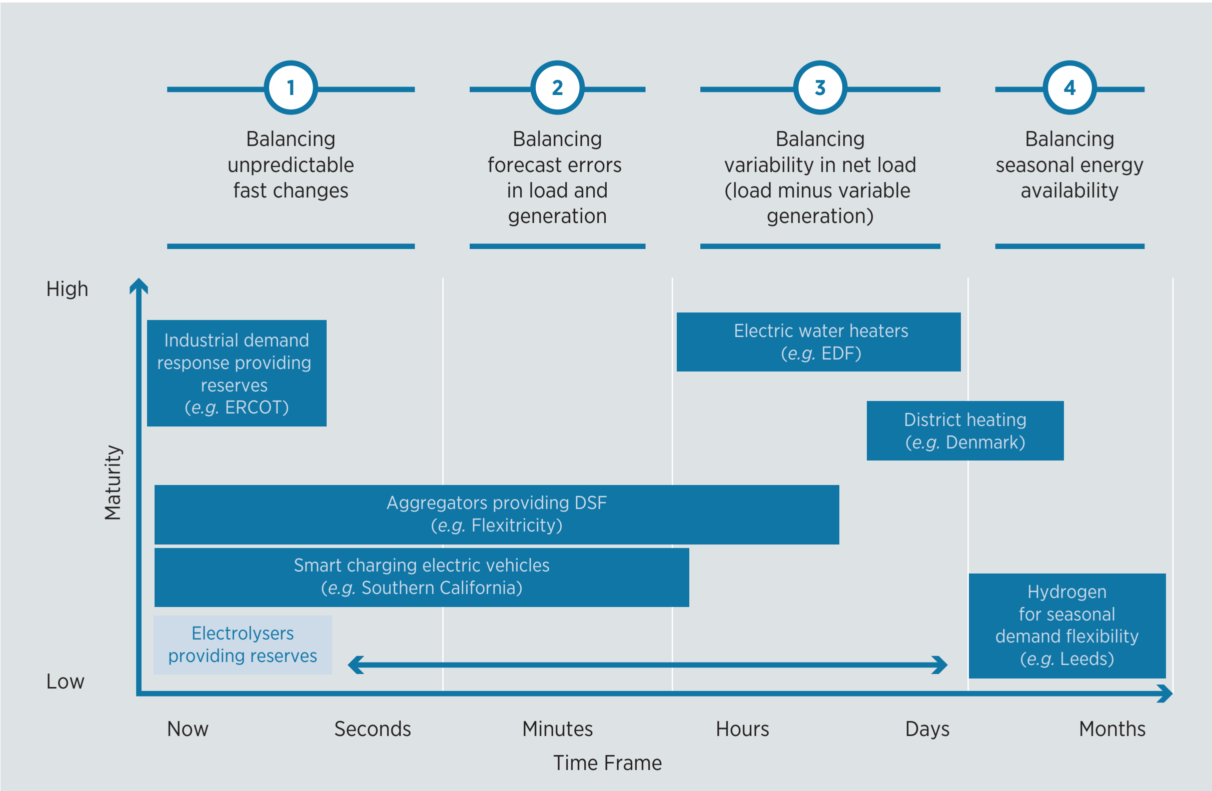
3. EXAMPLES OF DEMAND-SIDE FLEXIBILITY IN ACTUAL PRACTICE

Based on mapping technologies by end-use sector and reviewing the current status of demand-side flexibility, six real applications were selected. These real applications use one or more technologies from those presented in Section 2 and are applicable to one or more end-use sector (industrial, commercial and/or residential). Selected applications of demand-side flexibility will have an impact across different time scales and are characterised by different maturity levels. Figure 7 shows six examples of applications, classified by time scale and maturity.

Demand-side flexibility can impact all time frames from the very short term (*e.g.*, ERCOT's industrial demand response that can respond in sub-seconds) to the long term (*e.g.*, storing hydrogen for seasonal demand flexibility in the monthly time frame). With regard to maturity, while some applications are still being tested (*e.g.*, smart charging of EVs or hydrogen for seasonal demand flexibility) others like electric water heaters or industrial demand response have been used for a long time.

In the sub-sections that follow, these real applications of demand-side flexibility, shown in Figure 7, are discussed in more detail. Note that electrolysers providing reserves and hydrogen for seasonal demand flexibility are both considered as a single case representing demand-side flexibility based on hydrogen.

Figure 7 Demand-side flexibility real applications classified by technological maturity and flexibility time scale



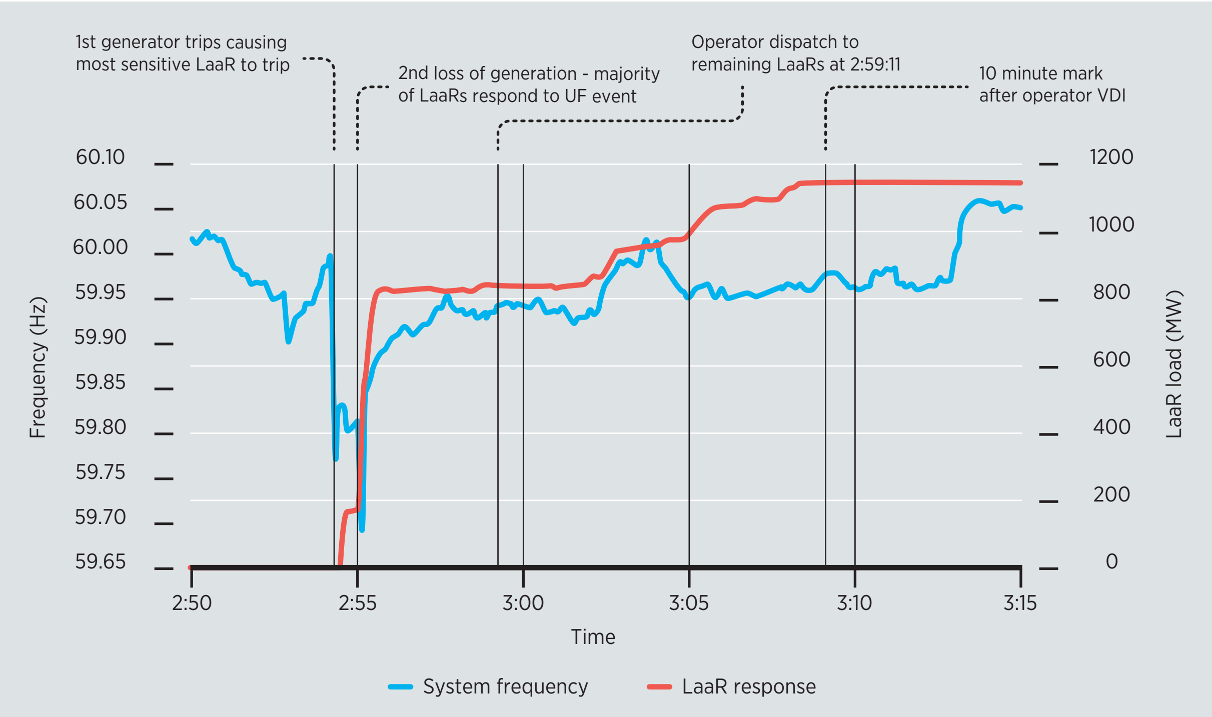
3.1 Industrial demand response providing reserves

ERCOT has allowed the participation of demand in the ancillary services market since 2002. That year electricity markets in Texas were opened to competition and large industrial customers were encouraged to participate in the ancillary services market. ERCOT allowed up to 25% of load resources to participate in the responsive reserve service (RRS).[13] Since 2002 the maximum share for load participation in RRS has been increased several times, to 50% in 2005 (VRE penetration was less than 2%) and 60% in 2018 (VRE penetration, mostly wind, was around 19%). The RRS boosts VRE integration by helping to compensate for the imbalances produced by these sources that would otherwise endanger system stability.

A great majority of load resources that provide RRS are from the industrial sector (for example, chemical plants, air separation plants, natural gas compression sites, oil fields and others), with very few large commercial sites such as data centres. In 2018, ERCOT had in total 300 load resources registered to participate in RRS accounting for a total capacity of 4 200 megawatts (MW)[14] (Matevosyan, 2018).

These loads can quickly respond to any request from the system operator and help balance the frequency of the system under large contingencies that take frequency down to 59.7 Hertz (Hz)[15], which in ERCOT usually happens once or twice per year. This is shown in Figure 8, which illustrates how load resources responded to a loss of generation in the ERCOT system on 22 December 2006.

Figure 8 ERCOT load resources providing RRS to stop frequency from decreasing



Source: Huang et al., 2007

13 In Europe, this is known as frequency containment reserve (FCR) or primary reserve.

14 Note that the peak demand in ERCOT during 2018 was 73.308 MW; thus, registered load resources account for 6% of total peak demand.

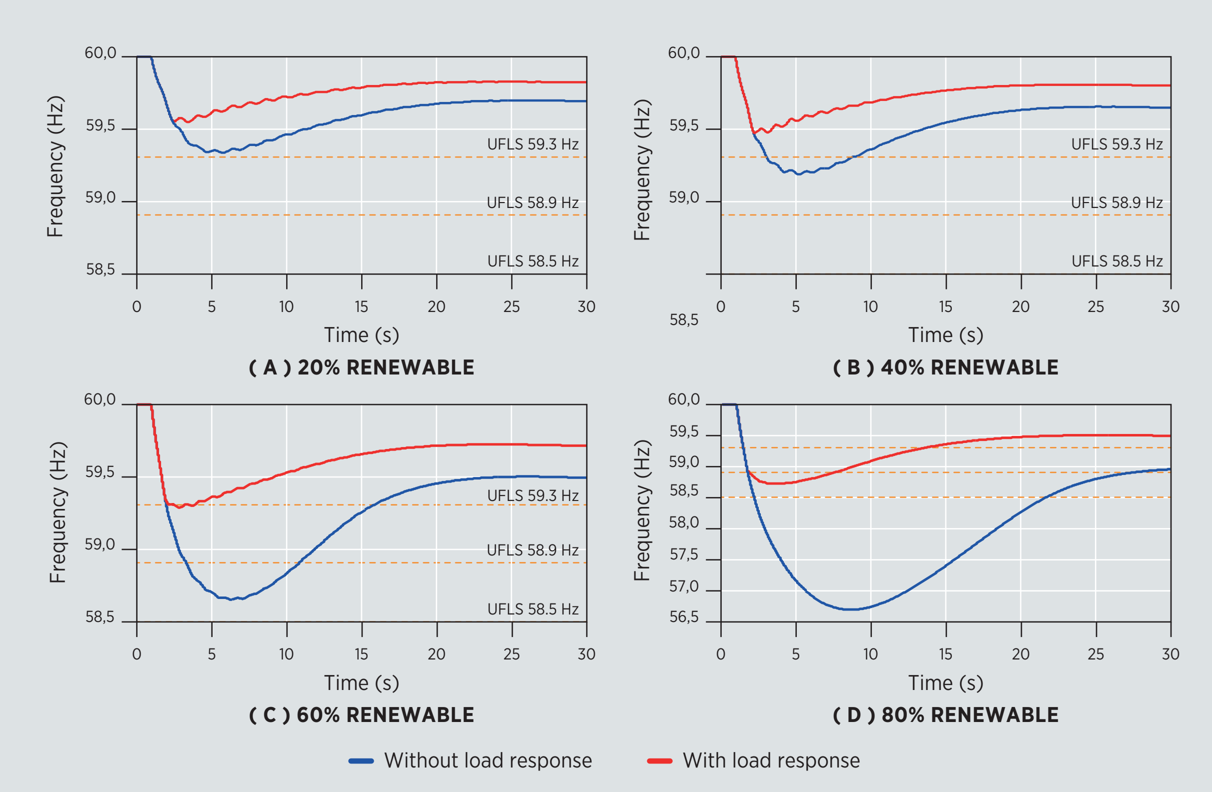
15 This frequency limit depends on the frequency trigger, which is by design low since load resources do not want to be tripped too often. Theoretically (not aligned with today's reality in ERCOT) if the industrial process is "ok" with tripping more often the frequency trigger can be set higher.

On 22 December 2006, the ERCOT power system experienced a 1 000 MW generation outage that caused the frequency to drop below 59.7 Hz. At this moment loads acting as a resource[16] (LaaR) responded in order to stop the frequency decline. Once the decline had been captured, the operator deployed the remaining LaaR manually to restore the frequency.

Apart from this, on 12 February 2019, ERCOT approved a modification of the ancillary services market that will include a fast frequency response (FFR) sub-product of RRS. This new service will be triggered at 59.85 Hz with full response in 0.25 seconds and a sustained time of 15 minutes. Additionally the 10-minute component of RRS will be unbundled into a separate service called ERCOT Contingency Reserve Service where load resources with or without under frequency relay (UFR) will be able to participate (Matevosyan, 2019). Some simulations on how an FFR product can be delivered by load resources are shown in Figure 9 (Liu *et al.*, 2019).

The Figure shows that when using demand-side flexibility to provide services such FFR (red line), the frequency nadir[17] is increased, and frequency is maintained within higher levels than when no load resources are used (blue line). This effect is more prominent as the non-synchronous penetration increases and system inertia decreases (see the distance between the blue and red lines in each of the plots as the renewable penetration increases). Providing FFR with load resources, therefore, appears to be highly efficient.

Figure 9 Load response providing fast frequency response in ERCOT under different renewable energy penetrations



Source: Liu et al., 2019

Note: UFLS: under-frequency load shedding

16 Now referred to as load resources. ERCOT no longer uses the term "load acting as a resource" (LaaR).

17 The frequency nadir is the minimum frequency level that is reached in a power system after a contingency (Teng et al., 2015). The goal of the system operator during a contingency is to prevent the frequency nadir from dropping below a pre-defined level that would trigger emergency load disconnection or even lead to a blackout.

3.2 Residential electric water heaters

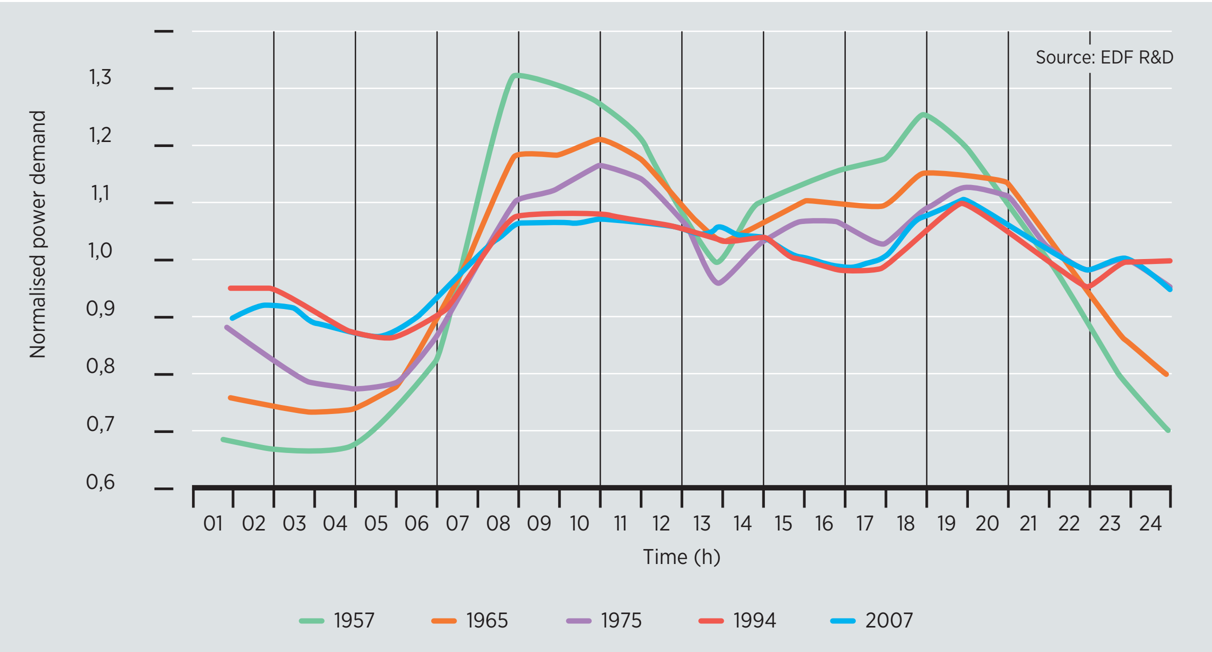
For a long time, residential consumers in France have been installing electric water heaters at home to cover their demand for hot water. According to Électricité de France (EDF), more than 13 million of these heaters are now installed in households around the country (Epiard and Prestat, 2017), representing around 50% of residential hot water systems (the rest are supplied by gas and oil heating systems). These 13 million electric water heaters have an annual consumption of 20 TWh and a peak demand of 8 GW, which occurs during early evening periods in winter. This demand, given the characteristics of the heaters, can be flexible if price signals are reflected in retail tariffs.

The majority of households in France have time-of-use tariffs that are also called "peak/off-peak" hours tariffs, because they pay a higher price during peak demand hours and lower prices during off-peak demand hours (Béjannin *et al.*, 2018). These tariff schemes incentivise consumers to use the electric water heaters to heat water during off-peak hours and to avoid peak hours. This has been a main factor behind the reshaping of the French demand curve since the 1950s, as illustrated in Figure 10, which shows the shape of the daily demand curve in France between 1957 and 2007. Over the course of those five decades, the deployment of electric water heaters together with a simple on/off control, encouraged a gradual shift in electric water heating demand to off-peak periods, progressively flattening the demand curve.

The demand-side flexibility inherent in electric water heaters, apart from flattening the French demand curve over the years, has also flattened electricity prices by heating water during low-price/low-demand periods instead of during high-price/high-demand periods. Nowadays electric water heaters foster VRE integration by heating water during periods of high VRE penetration and low prices.

French households are increasingly investing in heat pump water heaters, given that heat pumps have a higher coefficient of performance than direct electric heating (with one unit of electricity typically providing 4-5 units of useful heat). For instance, according to Cauret (2016), heat pump sales in France grew by 60% between 2011 and 2014, with around 73 000 residential heat pump water heaters sold in 2014. Additionally, EDF is testing how heat pumps and other residential devices can provide demand-side flexibility in the company's "concept grid" facilities in Le Renardieres, where the main goal is to test how a smart grid would work in reality.

Figure 10 Impact of residential electric water heaters on the daily load curve of France



Source: Epiard and Prestat, 2017

3.3 Demand-side flexibility through aggregators

As explained in Box 2, aggregators can be a critical actor to enable demand-side flexibility in all end-use sectors by operating a virtual power plant, which is an aggregation of different distributed energy resources. Today there are several industrial and commercial aggregators; however, in the residential sector, where aggregators could be a key enabler, the provision of demand-side flexibility is still at a pilot project level.

In the US, CPower is an example of a demand response aggregator that serves commercial and industrial consumers, so that they can provide demand-side flexibility to the grid by reducing demand. CPower thus acts as an intermediary between the consumer and the grid. When the grid is stressed, the aggregator sends a notification to shed load and the consumer gets paid for the total energy that was not used. Additionally CPower operates energy management software that allows the consumer to bid in the day-ahead and real-time markets (CPower, 2019). As of 2018, CPower had 3 500 MW of demand resource enrolled at 9 000 different sites across the US, and the company envisions that the total addressable market for demand response will grow from USD 1 080 million in 2017 to around USD 5 000 million in 2030 (Tipton, 2018).

In the United Kingdom (UK), Flexitricity is a demand response aggregator that serves industrial and commercial customers. This aggregator monitors electricity markets and consumer sites' capabilities continuously and seeks the most profitable revenue opportunities. It allows customers to participate in frequency response services, triad management[18], distribution management services and capacity markets. Flexitricity was the first demand response aggregator to enter the UK's capacity market and allows the resource to participate in different auctions (Flexitricity, 2019). The aggregator now has a portfolio of more than 450 MW composed of batteries and demand resources, and as of June 2018 Flexitricity claimed that it had generated GBP 20 million in savings for its customers since it started operating more than a decade ago (Gourley, 2018).

Actility is another example of a demand response aggregator. Operating in Belgium and France, this aggregator uses the Internet of Things to manage industrial and commercial load as well as distributed energy resources. For example, Veolia is using Actility in his pumping stations and water treatment plants. In these facilities Actility controls remotely the electrical devices and operates them in order to minimise the cost of electricity while ensuring operational limits. Additionally, Actility allows them to participate in grid balancing services (Actility, 2018).

Other aggregators that are enabling demand-side flexibility include, for example, ENERNOC (now owned by Enel), which is currently the lead demand response aggregator in Japan; Next Kraftwerke, which operates in several countries around Europe; REstore, which is an industrial, commercial and residential demand flexibility aggregator; PowerHouse Generation, which operates flexible loads in Ireland and New Motion, which is an EV aggregator.

On the residential side, the aggregators existing today typically only consider distributed solar PV and batteries in their portfolios. Aggregators could enable demand-side flexibility from residential power-to-heat, EVs or smart energy appliances as well; however, this is still in an experimental phase and only pilot projects can be found in practice.

18 Triads are the three half-hour periods of highest demand on the UK electricity transmission system between November and February. During these periods, network charges are exceptionally high for commercial and industrial customers; however, with triad management during these periods customers can reduce their consumption and consequently their electricity bill. This also reduces the need for investment in new infrastructure in the power system.

3.4 Electric vehicles with smart charging

As presented in Section 2.3, EVs can be a very important source of demand-side flexibility, but only if smart charging is enabled. There are currently many real cases of EV smart charging using both unidirectional and bidirectional charging.

Unidirectional smart charging (V1G) allows EVs to adjust their charging level based on market signals. In Southern California, Honda, Southern California Edison and eMotorWerks developed the SmartCharge programme that uses price signals to identify periods in which a high amount of renewable energy is available at the lowest cost. The EV user determines when the EV will be connected to the grid to charge by using an app, and then the system determines the best time to charge and at which level. Under this programme, the EV demand will be shifted in real time without impacting the consumer and will minimise the cost of grid upgrades (Hanley, 2018).

This has been already applied by CAISO, where through the 6 000 EV chargers that eMotorWerks aggregates, a 30 MW virtual battery is created. Here, EVs were used to reduce the system's load during periods when CAISO reached the price cap and to shift it to the lowest-cost intervals (Schachter, 2018).

Vehicle-to-grid (V2G) allows EVs to both adjust the load based on price signals and feed energy back to the grid. Nuvve, using the V2G concept first introduced by Kempton and Letendre in 1996 (Kempton and Letendre, 1997), is the first V2G technology company (Nuvve, 2019). Nuuve has implemented many V2G projects in different countries, but the company's first commercial project to date was launched in Denmark in 2016, in collaboration with Nissan and Enel. Under this project Nuvve installed 10 V2G chargers in the headquarters of the Danish utility Frederiksberg Forsyning with a maximum power of 10 kilowatts each. The chargers are all aggregated under one platform that allows the EVs to become active participants in Denmark's power system (Nissan, 2016).

Many examples exist of both unidirectional and bidirectional smart charging for electric vehicles

Figure 11 eMotorWerks smart charging app

Source: eMotorWerks, 2019

Other interesting ongoing V2G projects are those developed by TenneT in the Netherlands, using the aggregator Vandebron. Vandebron aggregates a fleet of EVs to provide automatic frequency restoration reserve (aFRR) to the TenneT grid. To do so, the aggregator temporarily stops and restarts the charging sessions of customers with EVs. This service is facilitated mainly to Tesla drivers, who receive a payment in exchange. For now, Vandebron claims to make bids into the aFRR service every day with a fleet of 150 Teslas. The aggregator is also exploring the use of blockchain technology to bid in the market (TenneT, 2019b).

An increasing number of EVs is expected to be deployed worldwide (1 166 million by 2050) according to the REmap global energy transformation scenario, which will contribute to a significant increase in global electricity demand. Under this scenario, unlocking demand-side flexibility with projects like the ones presented in this section will become very relevant for the power system. Smart charging, however, requires further on-site testing and research to fully understand its costs and value (for example, by better understanding the battery degradation and depreciation costs of V2G).

3.5 District heating systems

Denmark has among the highest numbers of district heating networks in Europe, and these systems currently supply around three-quarters of the country's demand for space heating. In these networks the centralised heat generation uses a variety of fuels, such as biomass, waste and natural gas. Additionally, because they are centralised, district heating networks allow the injection of heat that otherwise would be wasted.

Denmark's main generation technology for district heating is CHP. However, heat is also obtainable from geothermal and solar sources, as well as from renewable electricity using heat pumps or electric boilers. Surplus heat from industry can also be used in the district heating network. Thus, district heating networks basically act like giant thermal energy storage devices that store energy from different sources (Dansk Fjernvarme, 2016), and this thermal capacity can increase when combined with the latent thermal storage capacity from buildings (BINE Informationdienst, 2009).

In Danish district heating networks CHP plants are typically seen as a source of inflexibility. CHP plants produce both heat and electricity.

Figure 12 Vehicle-to-grid facilities at Frederiksberg in Denmark

Source: Nuvve, 2017

The production is driven by heat demand, and the electricity generated is sold in the wholesale market. The issue is that with high instant penetrations of VRE, market prices tend to be extremely low and CHP electricity output is squeezed out of the market. Given that heat generation cannot be reduced (it needs to cover heat demand), this is a source of inflexibility that can potentially cause VRE curtailment.[19]

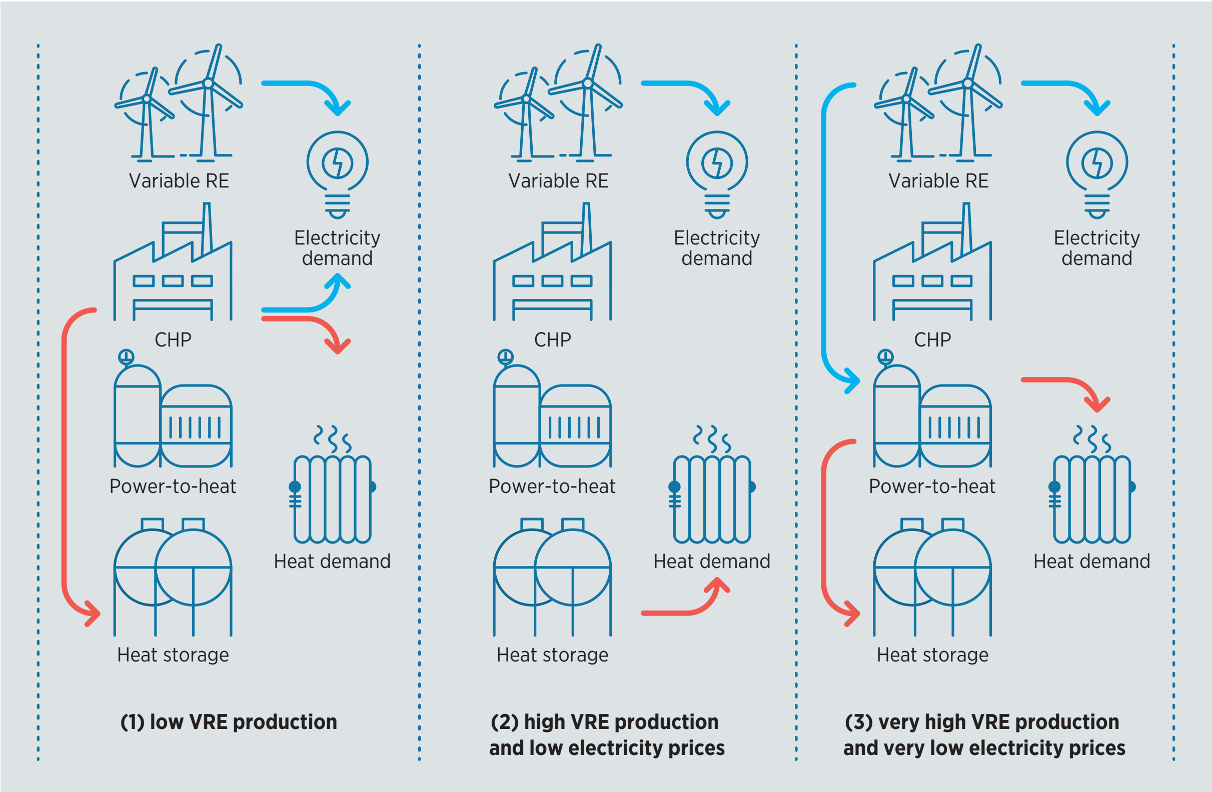
However, if coupled with heat pumps, water heaters, electric boilers or thermal storage, the flexibility of these CHP plants will increase, enabling them to provide balancing services (Bach, 2011). When coupled with heat pumps or electric boilers, CHP could generate electricity (and heat) when electricity prices are high and use electricity for heat generation when electricity prices are low. This heat could be either injected to the district heating network or stored for later use through some kind of thermal storage.

Figure 13 shows graphically how this would work. Note that CHP plants can also operate in heat-only mode, in which case there would be no electricity generation and no impact on the power system.

Additionally, by 2016, district heating systems in Denmark had 400 MW of electric boilers installed and only a small number of large-scale heat pumps, given that these are characterised by higher upfront costs and lower electricity cost. However, the country is planning to increase the number of centralised heat pumps given their higher efficiency compared to electric boilers.

By the end of 2019 Denmark expects to install 13 large heat pump projects at 11 CHP plants with a combined capacity of 29.7 MW, as the country did in the past with electric boilers. This will supply heat to 29 000 households, displace the use of fossil fuels and increase the utilisation of VRE power (Decentralized Energy, 2018).

Figure 13 Unlocking the flexibility of district heating

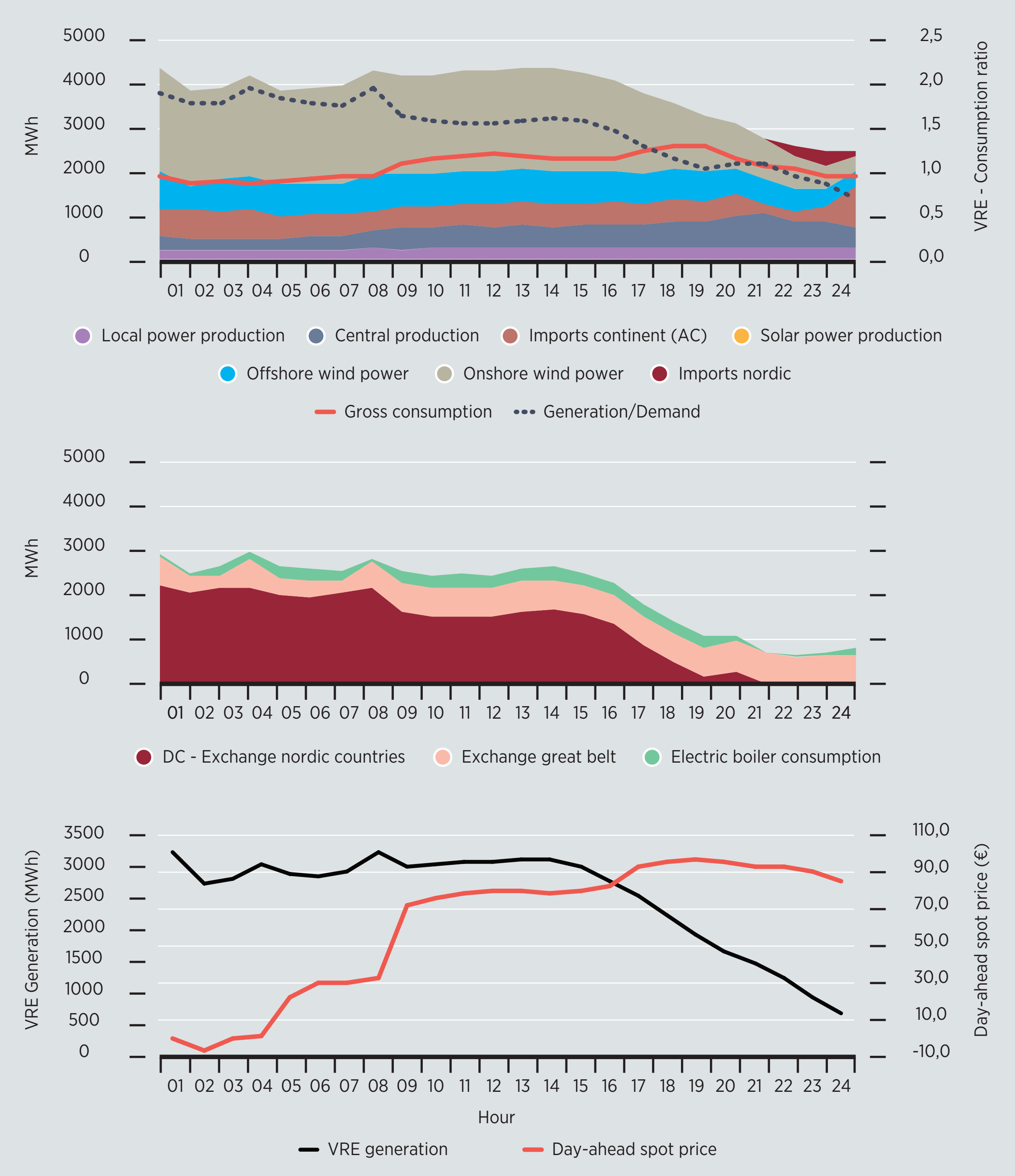


Source: Sneum et al. (2016)

19 This is the case of heat-driven CHP plants. If electricity driven, the CHP unit would be forced to reduce its combined generation.

knowledge framework for transforming the power sector (IRENA, forthcoming-b) presents Denmark as a major case study and uses real data from western Denmark to show how electric boilers react to price signals and provide demand-side flexibility. Figure 14 shows that when wind penetration is high and market prices are low, electric boilers are almost at full capacity; however, when wind penetration decreases by the end of the day, market prices increase and electric boilers reduce their electricity consumption. In this case, heat would come from a CHP plant or from a thermal storage in which heat was stored when electricity prices were low.

Figure 14 i) Overall energy balance, ii) exports and demand response and iii) day-ahead spot prices on 25 November 2015 in western Denmark



Source: IRENA, forthcoming-b using data from Energinet

3.6 Demand-side flexibility using hydrogen production (seasonal and short term)

Hydrogen is an energy carrier that could help decarbonise those energy sectors that would be otherwise difficult to decarbonise through electrification (IRENA, 2018b). Hydrogen could help decarbonise industry, buildings (through injection into the gas grid) and transport. Additionally, hydrogen can be produced from excess VRE generation and can be stored in existing natural gas networks or in specific hydrogen storage facilities, thus providing seasonal demand flexibility. Currently, no large-scale hydrogen projects are in operation; however, some feasibility studies and pilot projects such as H21 Leeds City Gate and H21 North of England have been initiated.

The H21 Leeds City Gate project aims to determine the technical and economic feasibility of converting the natural gas network in Leeds to 100% hydrogen (Northern Gas Networks, 2017). The report concludes that current gas networks have adequate capacity for conversion, they can convert incrementally with minimal disruption to customers, and minimal new infrastructure will be required. The project will also include hydrogen storage that will enable inter-seasonal demand flexibility, which is difficult for sectors where direct electrification is considered (for example, the heat sector).

The H21 Leeds City Gate project was expanded in November 2018 to the H21 North of England project, which aims to convert all of the gas networks in the north of England to hydrogen by 2034. The project will imply a 125 GW hydrogen transmission system with 12.5 GW of hydrogen production capacity and 8 TWh of storage (equivalent to 62 Hornsdale Power Reserve battery systems – the Tesla 100 MW/129 MWh battery in South Australia), which will be capable of providing seasonal demand-side flexibility (Northern Gas Networks, 2018).

These projects, however, consider hydrogen production via steam methane reforming coupled with carbon capture and storage, which would not be directly relevant for VRE integration. However, if it proves to be economically and technically feasible in the future, electrolysis will be considered as an alternative hydrogen production method in both projects. In this case, apart from the provision of seasonal demand flexibility (which is enabled by the gas network conversion and hydrogen storage), the electrolysers could provide ancillary services such as FCR or frequency restoration reserves (FRR).

Although this benefit has yet to be demonstrated in practice, electrolysers are proven to have fast ramping capabilities that enable them to provide primary reserves (Thyssenkrupp, 2019). Additionally in research papers such as Suárez *et al.* (2018) the authors have simulated how a 300 MW electrolyser in the Netherlands would perform when providing FCR and FRR to the grid, with satisfactory results.

Box 3 Modelling demand-side flexibility with the IRENA FlexTool

To analyse the value of demand-side flexibility, optimisation techniques are required. The 2018 report *Power system flexibility for the energy transition* (IRENA, 2018a) found that flexibility has to be sought not only on the supply side but also on the demand side. The IRENA FlexTool, a freely available tool linked to the report, performs both capacity expansion and dispatch with a focus on power system flexibility.

The **IRENA FlexTool** allows the analysis of all the different sources mentioned in Section 2 of this analytical brief, namely:

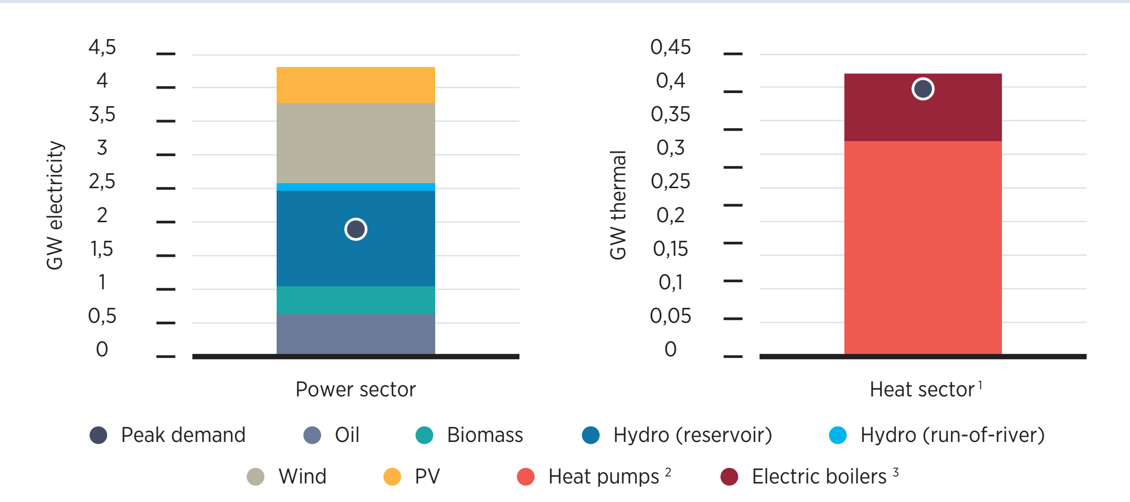
- **Power-to-heat**, by modelling heat pumps with a COP that depends on temperature or modelling thermal energy storage.
- **Power-to-hydrogen**, by modelling electrolysers.
- **Electric vehicles**, by introducing time series of vehicles connected to the gird at every time period with the possibility to model vehicle-to-grid (V2G).
- **Generic load shedding/shifting** from industrial loads or residential appliances by modelling it as generation in case of decreasing demand and negative generation in case of positive demand.

The tool can not only analyse how demand-side flexibility operates in a given system but also assess the optimal amount of it if the required information is available. For example, given the power system information and heat demand, the tool could analyse the amount of heat pumps that could be profitable to install and compare them with other options such as gas or electric boilers.

EXAMPLE: Power-to-heat

Assuming a power system with the following installed capacity and peak demands in the electricity and heat[1] sectors:

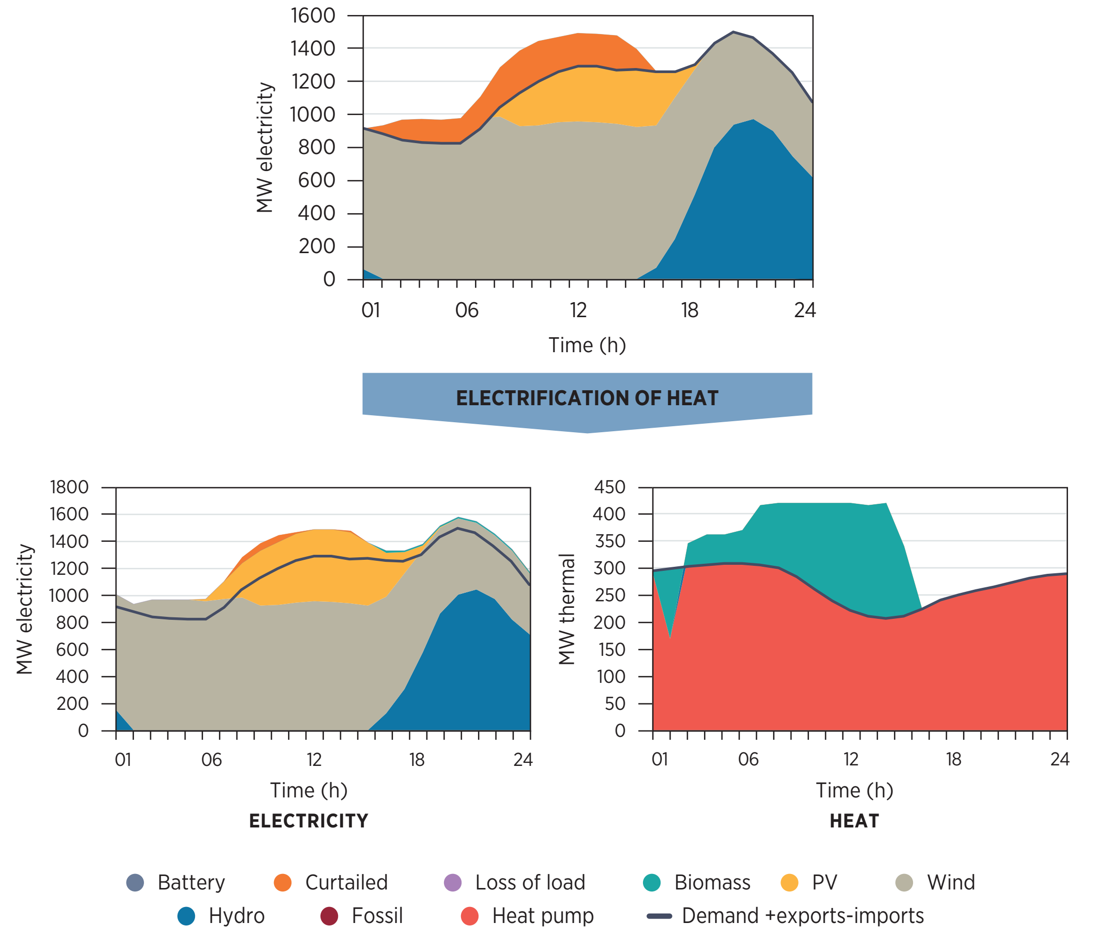
Figure 15 Installed capacity and peak demand in the electricity and heat sectors of the system chosen



1 In the heat sector there is thermal storage that can store up ti 2 GWh of heat
2 The electric boilers produce 1 unit of heat per unit of electricity
3 The heat pumps have a COP of 3.2 which means that with 1 MW of electricity they can generate 3.2 MW of heat

1 Heat demand profile was estimated according to Connolly et al. (2015) and assuming a peak of 400 MW. The result is a seasonal profile that has a peak in winter and its minimum demand during summer months (June, July and August)

Figure 16 Effects of electrifying heat using a representative day with high penetration of VRE



An entire year is simulated first considering that the power sector is independent from the heat sector and then considering that both sectors are coupled. The results, using a representative day with high penetration of VRE, are shown in Figure 16.

The figure shows how the VRE generation that would be curtailed is converted into heat when sector coupling is implemented. When sectors are decoupled the VRE curtailment in the system is 19.5% of the total VRE generation, while if the heat sector is electrified this curtailment is reduced to almost zero.

Beyond what the figures show, heat demand could also be met, when both sectors are decoupled, through gas boilers. They, however, produce carbon emissions. When heat demand is electrified or met with heat pumps, emissions can be reduced not only in the power sector (through higher integration of VRE with demand-side flexibility), but also in the heat sector, by avoiding gas boilers.

The IRENA FlexTool can go deeper into the analysis of sector coupling and demand-side flexibility, but this example shows how demand-side flexibility could be beneficial to foster VRE integration and advance the energy transition.

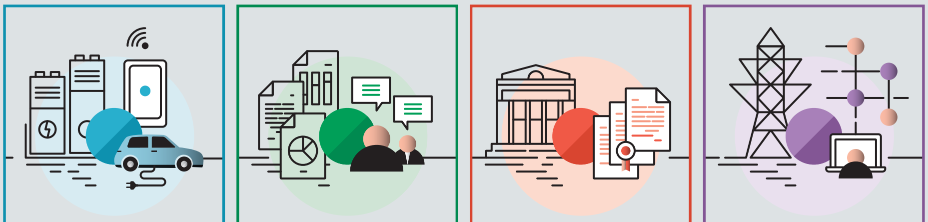
4. INNOVATIONS THAT ENABLE DEMAND-SIDE FLEXIBILITY APPLICATIONS

The examples presented in Section 3 describe either solutions already implemented or pilot projects involving comprehensive research and testing. These pilot cases, however, need require new enabling technologies, business models, market design or system operation innovations to support implementation at scale. The *Innovation landscape for a renewable-powered future* (IRENA, 2019b) proposes a toolbox of 30 key innovations to transform the power sector across four dimensions: enabling technologies, business models, market design and system operations.For each example presented in the previous section, a set of these innovations can be combined to facilitate demand-side flexibility implementation. Figure 17 shows the main innovations that enable each demand-side flexibility example from Section 3.

Figure 17 is intended to be read from left to right analysing the different innovations that could enable each use case. An example can be done using, for instance, EVs with smart charging. The relevant **enabling technologies** for this are EV smart charging, the Internet of Things, and artificial intelligence and big data. Possible **business models** that could enable these technologies are aggregators and pay-as-you-go models. In terms of **market design**, time-of-use tariffs, innovative ancillary services or market integration of distributed energy resources could improve the flexibility that EVs can provide to the power system. Finally, possible innovations in **system operations** would include co-operation between distribution and transmission system operators, changing future roles for distribution system operators and virtual power lines.

Note that this is only a toolbox of innovations that could be useful to guide policy makers in the implementation of solutions for a renewable-powered future (in this case, to enable demand-side flexibility). However, identifying which would be the optimal pathway is a more complex topic that IRENA addressed in its *Power sector transformation knowledge framework* (IRENA, forthcoming-b), which maps existing measures in front-runner countries that could be replicated in others experiencing challenges to achieve high shares of renewable energy in the system.

Figure 17 Mapping different demand-side flexibility examples with innovations from the IRENA *Innovation Landscape* report



	ENABLING TECHNOLOGIES	BUSINESS MODELS	MARKET DESIGN	SYSTEM OPERATION
Industrial demand response providing reserves	• Renewable power-to-heat • Renewable power-to-hydrogen • Behind-the-meter batteries • Artificial intelligence and big data	• Aggregators	• Innovative ancillary services	
Electric water heaters responding to prices	• Renewable power-to-heat • Internet of things • Artificial intelligence and big data	• Aggregators	• Time-of-use tarifs	• Co-operation between transmission and distribution system operators • Future role of distribution system operators
Aggregators enabling demand-side flexibility	• Behind-the-meter batteries • Electric vehicle smart charging • Renewable power-to-heat • Internet of things • Artificial intelligence and big data	• Aggregators • Energy-as-a-service	• Market integration of distributed energy resources	• Co-operation between transmission and distribution system operators • Future role of distribution system operators • Virtual Power Lines
Electric vehicles with smart charging	• Electric vehicle smart charging • Internet of things • Artificial intelligence and big data • Blockchain	• Aggregators • Pay-as-you-go models	• Time-of-use-tariffs • Innovative ancillary services • market integration of distributed energy resources	• Co-operation between transmission and distribution system operators • Future role of distribution system operators • Virtual Power Lines
District heating networks	• Renewable power-to-heat	• Community ownership models	• Increase time granularity in electricity markets	
Hydrogen for seasonal demand-side flexibility	• Renewable power-to-hydrogen		• Innovative ancillary services	• Advanced forecasting of variable renewable power generation

Source: Based on IRENA (2019b)

4.1 Enabling technologies

Enabling technologies are technologies that play a role in facilitating the integration of renewable energy. For demand-side flexibility purposes, the most relevant enabling technologies are:

Renewable power-to-heat, which includes heat pumps, electric water heaters and thermal energy storage as explained in Section 2.1.

Renewable power-to-hydrogen (IRENA, 2018b), which refers to the production of hydrogen from renewable energy by using an electrolyser, as explained in Section 2.2.

Electric vehicle smart charging (IRENA, 2019d), which includes home and public charging as explained in Section 2.3.

Behind-the-meter batteries (IRENA, forthcoming-c), which could enable demand-side flexibility in the residential and commercial sectors given their charging and discharging capabilities.

Others such as the **Internet of Things**, **artificial intelligence and big data**, and **blockchain**.

4.2 Business models

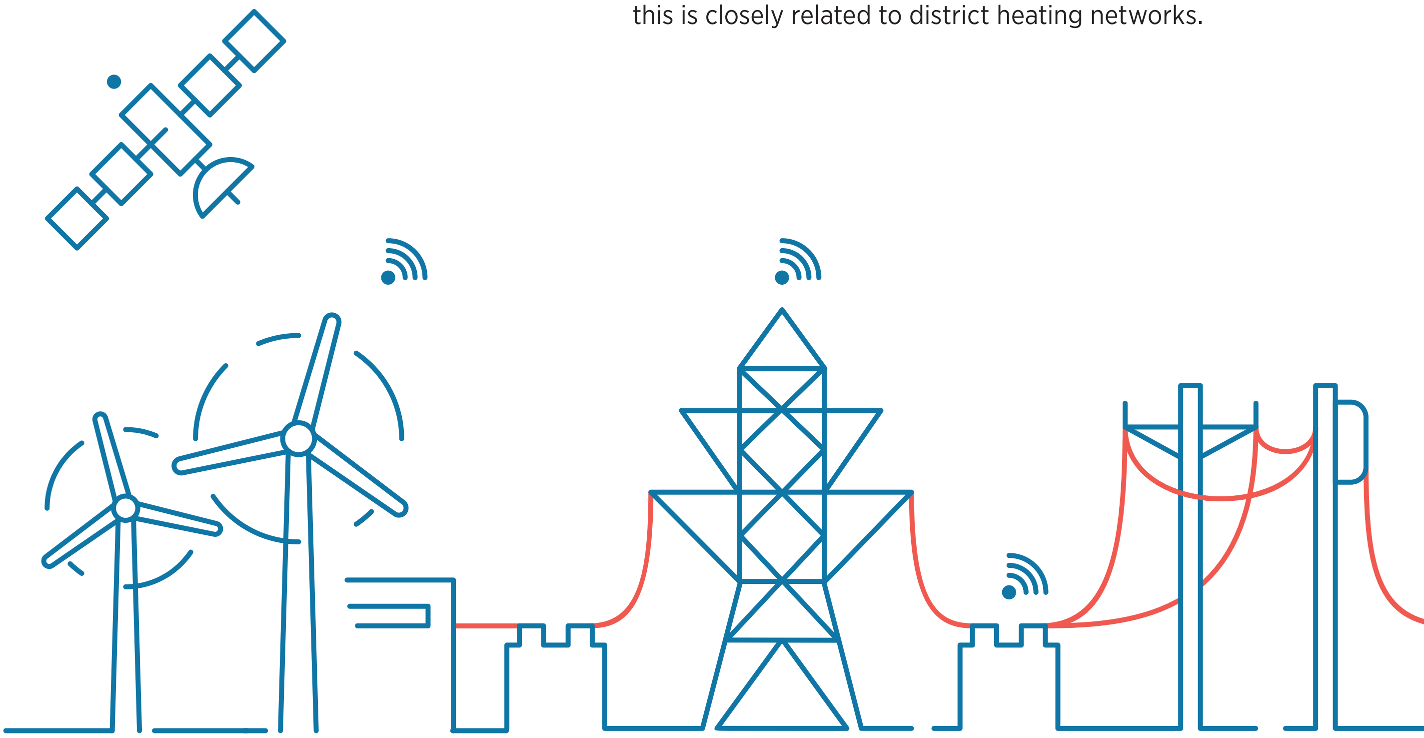
Business models are innovative models that create the business case for new services, enhancing the system's flexibility and incentivising further integration of renewable energy technologies. For demand-side flexibility purposes, the most relevant business models are:

Aggregators, whose role in enabling demand-side flexibility was explained in Box 1.

Energy-as-a-service, which refers to the shift from selling energy to selling the actual services that energy provides to customers (*e.g.*, indoor temperature profiles, mileage of EVs), given the increased potential of "behind-the-meter" demand-side management or energy storage. For instance, with energy-as-a-service demand-side flexibility in the residential sector can be automatically controlled in exchange for financial compensation.

Pay-as-you-go models, which consist of consumers paying directly for the services they use. These models could enable public charging of EVs.

Community ownership models, which refers to the collective ownership and management of energy-related assets. In terms of demand-side flexibility this is closely related to district heating networks.



4.3 Market design

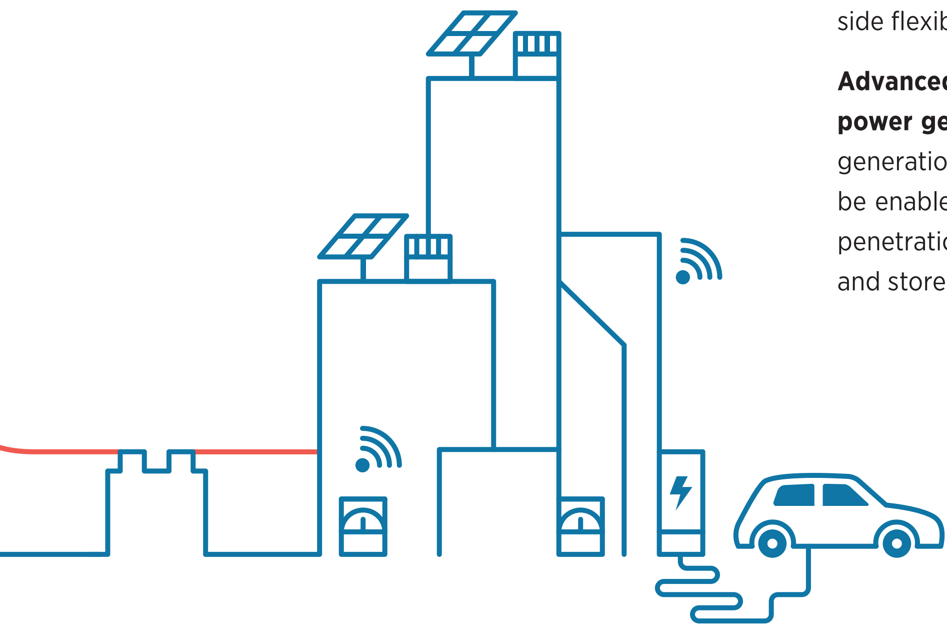
Market design refers to new market structures and changes in the regulatory framework to encourage flexibility and value services needed in a renewable-based power energy system stimulating new business opportunities. For demand-side flexibility purposes, the most relevant market design innovations are:

Time-of-use tariffs, which provide price signals to consumers about the least and most expensive times to consume electricity. Consumers will ideally respond by focusing their consumption on hours when prices are low and decreasing it when prices are high.

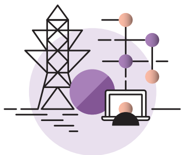
Innovative ancillary services, which will include demand participation and will allow demand to obtain revenues from the provision of ancillary services (*e.g.*, the new reserves scheme in ERCOT approved in February 2019).

Market integration of distributed energy resources, which enables these assets to participate in different markets such as wholesale markets or ancillary services markets.

Increase of time granularity in electricity markets could also incentivise demand to participate in different markets by better capturing flexibility in the system.



4.4 System operation



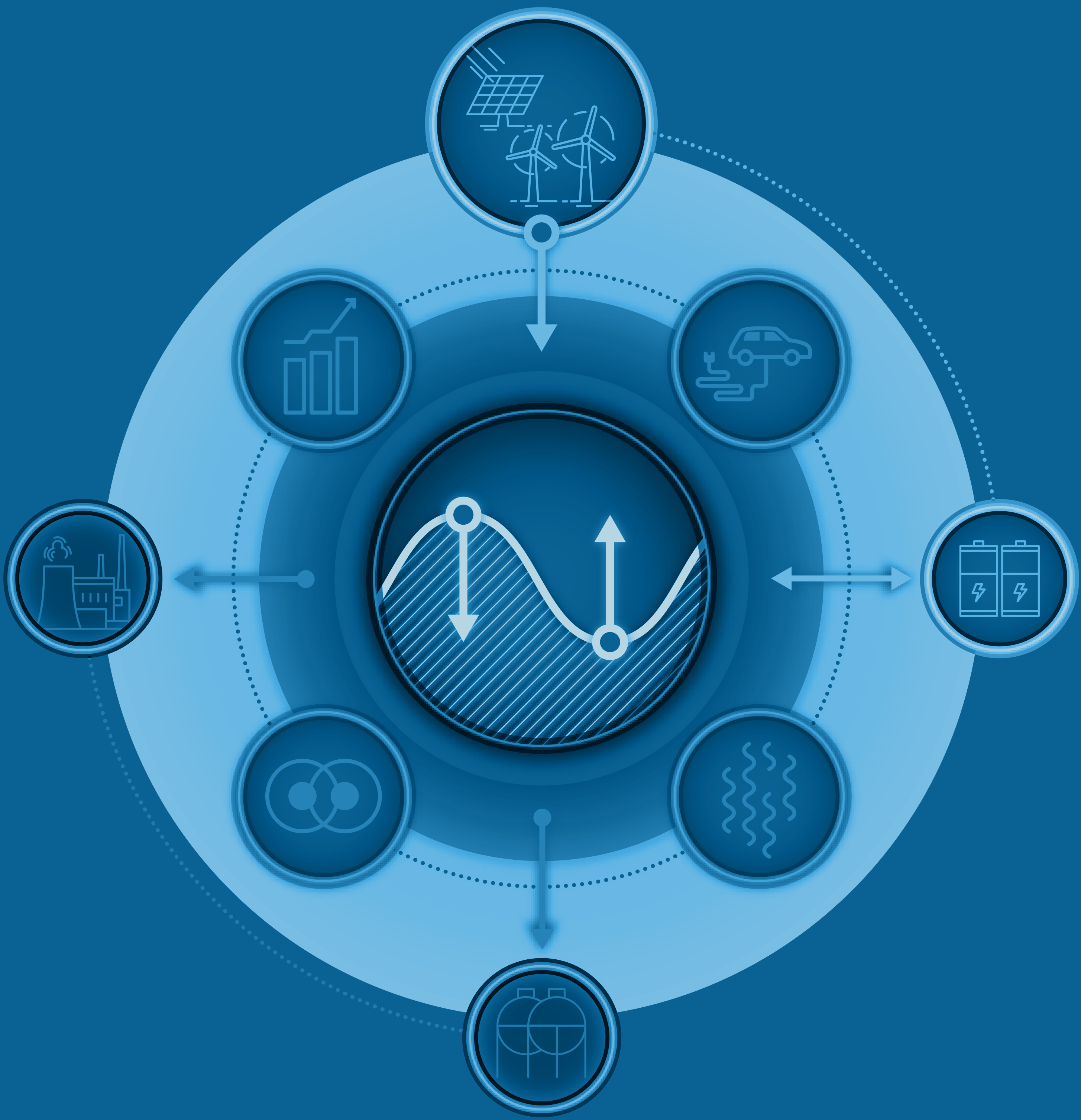
System operation refers to innovative ways of operating the electricity system, allowing the integration of higher shares of variable renewable power generation. For demand-side flexibility purposes, the most relevant system operation innovations are:

Co-operation between transmission and distribution system operators, so that there is a smooth connection between consumers and the transmission system operators that allows consumers to participate in all markets and facilitates the exchange of data, in a holistic view of the power system. This is highlighted by the European Network of Transmission System Operators (ENTSO-E) as one of the key enablers of demand-side flexibility (CEDEC *et al.*, 2019)

Future role of distribution system operators, in the sense that they should expand their role to procure grid services from distributed energy resources (including demand-side resources) and to operate them in order to optimise existing grids and defer investments.

Virtual power lines, which refers to transmission and distribution investment deferral. Demand-side flexibility can provide distribution investment deferral (for example, with aggregators or EVs shifting loads to times when the lines are less congested) and transmission investment deferral (for example, with hydrogen for seasonal demand-side flexibility).

Advanced forecasting of variable renewable power generation: by better forecasting the VRE generation, seasonal flexibility from hydrogen can be enabled. In times of the year when a high VRE penetration is expected, hydrogen can be produced and stored to be used throughout the year.



5. CONCLUSIONS

This brief has reviewed the concept of demand-side flexibility as a follow-up to IRENA's recent Innovation Landscape study, as well as another IRENA report, *Power system flexibility for the energy transition*.

As an asset in the ongoing transformation of power systems, demand-side flexibility fulfils several important aims:

1. It facilitates VRE integration by reshaping load profiles to match VRE generation;
2. It facilitates system-wide electrification by reducing peak load and managing seasonality; and
3. It reduces production costs by shifting load from periods with high price of supply to periods with lower prices.

Various solutions already exist to provide demand-side flexibility, namely power-to-heat, power-to-hydrogen, EVs, smart appliances and industrial demand response.

These solutions can be competitive or applicable in different end-use sectors (for example, power-to-hydrogen is only competitive to provide demand-side flexibility in the industrial sector via electrolysers) or in all of them (for example, power-to-heat can provide demand-side flexibility with heat pumps and thermal storage in the industrial, commercial and residential sectors), and at different time frames. To facilitate the implementation process of these solutions and unlock the full potential of demand-side flexibility, a set of innovations should be considered. These are described in more detail in IRENA (2019b).

The potential for demand-side flexibility, expressed as the sum of flexible load at each hour of the year, is high and, according to IEA (2018), is equal to 4 000 TWh (457 GW average) today and is expected to grow to 7 000 TWh (800 GW average) by 2040 due to the electrification of transport and buildings (mostly electrification of heat). While there are already parts of the world in which demand-side flexibility is being leveraged, there is still a long way to reach the full potential of this flexibility source. In this brief, six different demand-side flexibility applications were described. Testing and research must continue to provide a more complete understanding of this aspect of the global energy transformation.

In the coming years and with this brief as a starting point, IRENA aims to further investigate the role of demand-side flexibility in the global energy transformation. Continuing to map innovations will help to build up more knowledge, while system modelling will help to fully analyse the value of unlocking this important source of flexibility.

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