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FLEXIBILITY IN THE POWER SYSTEM

The need, opportunity and value of flexibility

SAFER, SMARTER, GREENER

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AC	Alternating Current
CAES	Compressed-Air Energy Storage
CCGT	Closed-Cycle Gas Turbine
CHP	Combined Heat and Power (production)
DC	Direct Current
DER	Distributed Energy Resources
EES	Electrical Energy Storage
FCR	Frequency Containment Reserve(s)
FRR	Frequency Restoration Reserve(s)
HVDC	High-Voltage Direct Current
LFC	Load Frequency Control
OTC	Over The Counter
P2G	Power to Gas
P2H	Power to Heat
P2L	Power to Liquid
P2P	Power to Products
P2X	Power to Anything
PHS	(Fixed-speed) Pumped Hydro-electric Storage
PV	Photo-Voltaic
RES	Renewable Energy Source(s)
RR	Replacement Reserve(s)
V-RES	Variable Renewable Energy Source(s)
VS-PHS	Variable-Speed Pumped Hydro-electric Storage
PTU	Programme Time Unit

EXECUTIVE SUMMARY

In the electric power system, electricity supply needs to be balanced with electricity demand and network losses at all times to maintain safe, dependable and stable system operation. Flexibility within the power system is required to compensate for variability in supply and demand and maintain its balance.

Historically, variability and uncertainty in the system mainly occurred on the demand side. This variability was to be matched top down through flexible conventional power plants and a reliable grid. The ongoing changes in energy production and consumption – creating more variability and uncertainty – ask for other means of flexibility in addition to the conventional ones. The main changes are the increase of renewable energy sources, both on large-scale and distributed level, and the increase in power consumption and demand variability by the electrification of the transportation and heating & cooling sectors. The latter also provide a means of flexibility, that is demand side management. This means that new power consumers, like electric vehicle chargers and electrical heat pumps, can respond to flexibility requests from the power system by adapting their consumption pattern. This new ecosystem creates the smart grid, where renewable energy sources, flexible consumers and energy storage systems cooperate.

The different sources of flexibility may have technological and cost-related barriers to prevent their uptake. There are also barriers in regulation, standardisation and energy market rules. However, regulations, standards and markets are being developed worldwide to facilitate emerging flexibility solutions, like energy storage and demand response. One of the standardisation initiatives is DNV GL's recommended practice on energy storage, GRIDSTOR. For most flexibility resources, especially energy storage, a single flexibility service will not ensure a positive business case. Stackable revenues, by combining operational services in different markets and time scales, are therefore important to render the business case worthwhile. DNV GL has developed the StRe@M model, which is able to assess and analyse the short and long term business case of flexibility resources whilst taking into account stackable revenues.
DNV GL's StRe@M model is able to capture and determine the stackable revenues of flexibility resources such as a Li-ion battery, demand response, a gas engine or a pumped hydro-electric storage plant. The StRe@M model optimises the portfolio of flexibility services, while considering uncertainty in the forecasts of the market prices and RES generation for the next hour(s), day(s), and longer periods.

This paper explains the need for flexibility in the current and future power system, and presents the types of services for flexibility, the available sources, the existing barriers for deployment, and the StRe@M method to calculate the business case for a combination of flexibility applications.

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WHAT IS FLEXIBILITY AND WHY DO WE NEED IT?

INTRODUCTION

In the electric power system, electricity supply needs to be balanced with electricity demand and network losses at all times to maintain safe, dependable and stable system operation. Flexibility within power systems is hence required to maintain this balance. Flexibility is defined in this paper as:

> “a service that provides capability to the electric power system to respond to fluctuations and uncertainty in supply and demand to maintain and restore stable and safe operation within the limits of the system”

This capability can be measured through, amongst others:

- the amount of adjusted power (increase or decrease) in generation or demand in reaction to economic or operational signals
- the speed of delivery and the rate of change of power, and
- the duration of the service
- the location of the point of connection

Flexibility is required to safeguard system reliability and safety with respect to variability in several dimensions, including different time scales and locations in the network. With the expected increase of variable renewable energy sources (RES) and electrification of energy-intensive industries, driven by international and national climate and energy plans, flexibility services are key to maintain the continuous balance between supply and demand within appropriate operational, safety and cost optimisation requirements.

The objective of this paper is to define the concept of flexibility within existing electricity systems, explain the increasing need for flexibility due to challenges faced by conventional systems, and present the various flexibility services and the resources that can provide these services. This paper concludes with case studies of flexibility services and their business case.

THE CONCEPTS OF ELECTRICITY SUPPLY AND FLEXIBILITY

Electricity is intertwined with all daily activities in industrialised countries. Conventionally, predominantly passive and inelastic end-consumers are supplied with electricity through large-scale technical infrastructure combined with a control platform that ensures balancing of supply and demand. The function of the technical infrastructure of the electricity system, consisting of power plants for electricity generation and transmission and distribution networks (i.e. the grid, including transformers, switchgear, lines and cables) for electricity transportation, is to supply electricity to the consumers. The control platform for balancing supply and demand, and the flexibility required to match generation and demand fluctuations are typically provided through a combination of services at different operational timescales before and during the time when balancing is required.

Figure 1 gives a schematic overview of the power system, with central power plants and the grid, and also emerging generation and demand assets, like renewable energy sources, electric vehicles and energy storage systems.

A specific property of electricity is that energy generation must be balanced with energy demand at any moment, while considering losses in the network. Traditional balancing is provided through predicting the electricity demand in a following time frame and scheduling the operation of generation units accordingly. If system balance between supply and demand is not maintained, the operational system frequency (typically 50 or 60 Hz) will deviate from its reference, potentially leading to system instability and outages, see figure 2.

Therefore, also corrective balancing actions are needed in real time. Flexibility services in conventional systems can come in various forms to provide upward (increase generation/decrease load) or downward (decrease generation/increase load) regulation of frequency (i.e. frequency response) or to deal with contingencies (e.g. equipment failures or sudden demand drops) in the network. Small deviations within a certain interval are, however, allowed and occur continuously during normal system operation.

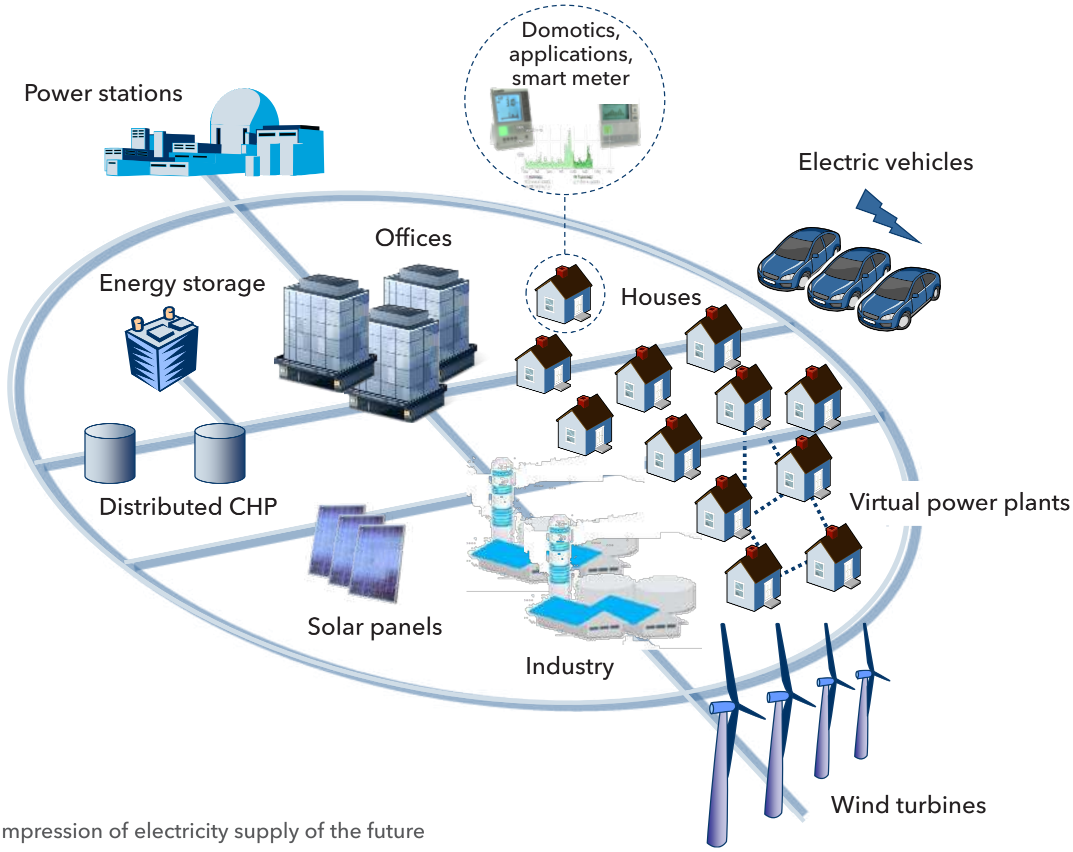


Figure 1 - Impression of electricity supply of the future

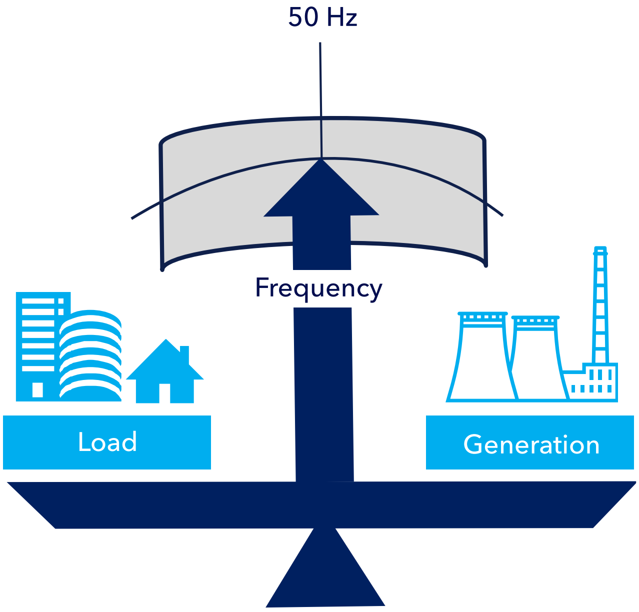


Figure 2 - Supply-demand balance and its impact on operational frequency

The supply-demand balancing platform of electricity systems includes long-term agreements (years before, for the purpose of seasonal and weekly generation planning), day-ahead scheduling (one day before), intra-day scheduling (during the day) and balancing (on short term (≤ 15 minutes) and/or real time). This platform can be organised in various forms. For example, the balancing platform can be set up as a vertically integrated utility that safeguards adequate system operation, or as a combination of different markets at different timescales, which is the case in liberalised electricity systems, see figure 3. In this figure, 'Clearing/gate closure' means the closure of the day-ahead electricity market, which is in general at 12 noon on the day before activation.

THE ROLES IN THE UNBUNDLED ELECTRIC POWER SYSTEM AND ELECTRICITY MARKETS

The electric power system consists of the grid and producers and consumers of electricity. The grid is managed by network and system operators: transmission system operator (TSO, high voltage levels), independent system operator (ISO, high voltage), distribution network operator (DNO, medium/low voltage). On the electricity wholesale markets (national or international, run by market operators, MO) the producers sell their energy to retailers (or suppliers), who in turn sell it to consumers (retail market). Apart from the wholesale, a lot of electricity is still traded bilaterally ('over the counter' or OTC). Traders are also active on the markets. The roles of producer, trader and retailer may be combined in one company. All parties active on the market must be balance responsible parties (BRP), this means they must have bought and sold equal amounts of energy at the moment of delivery, to keep their own supply-demand balance at all times. In some country's power systems, the roles of market parties and grid operators are combined, these companies are generally called utilities.

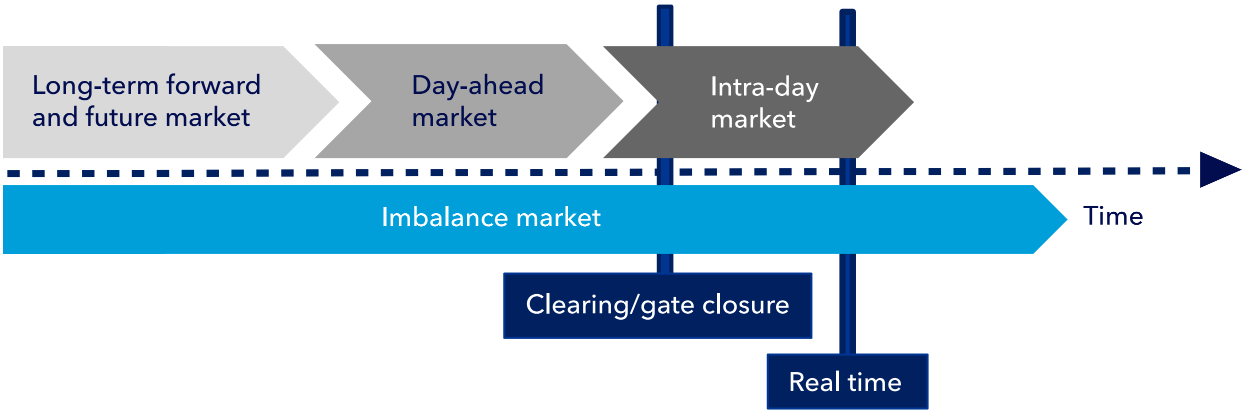


Figure 3 - Different operational markets in liberalised electricity systems

In all trade or control platforms, deviations will be restored using different reserves at different deviation levels and timescales. Within the European synchronised network (the ENTSO-E region), for example, these types of reserves are Frequency Containment Reserves (FCR), Frequency Restoration Reserves (FRR) and Replacement Reserves (RR). Other reserve classifications are used in other countries, such as spinning, non-spinning and replacement reserves, for example. When a frequency deviation (i.e. the indication of possible system imbalance) occurs, FCR aim to automatically ensure the deviation is contained. FRR are manually or automatically activated and used to restore the frequency to its reference level and free up FCR. RR are manually controlled reserves to replenish FCR and FRR, and are generally activated in or near the area of the disturbance or outage.
The functionalities and characteristics of the different reserves are summarised in figure 4. These reserves are usually delivered by generation resources. Flexibility can be provided from the generation side, but also from the demand side, from the grid or through system operation, as explained in the next chapter.

For a balanced system, the electricity generated by a combination of available units in the system needs to match demand at all times. The selection of units to be used (unit scheduling and commitment) is based on national regulations and/or on market rules, taking into account the predicted demand (in the short, middle and long term), the technical and economic characteristics of the units and grid constraints. Different types of power generation units have different characteristics based on their types of generation mechanisms and energy resources, determining their start-stop flexibility, minimum safe operational levels and ramping abilities when changing power. Some generators (like coal-fired and nuclear) have low running costs, but slow response times (several hours), therefore these are most suitable for continuous operation at maximum power. These are the base load generators. On the other hand, generators with low minimum stable operational levels and fast ramping rates are able to follow fast changes in demand, and can therefore be used for peak demand provision, this is a form of short term flexibility. Examples of peak-demand units are gas turbines (with relatively high running costs) and hydro-electric power plants. Units with properties between the base load and the peak load generators are called intermediate cycling units. During unit commitment and dispatch, the optimal mix of generation units is employed to meet the demand at each time unit. A schematic example is shown in figure 5.

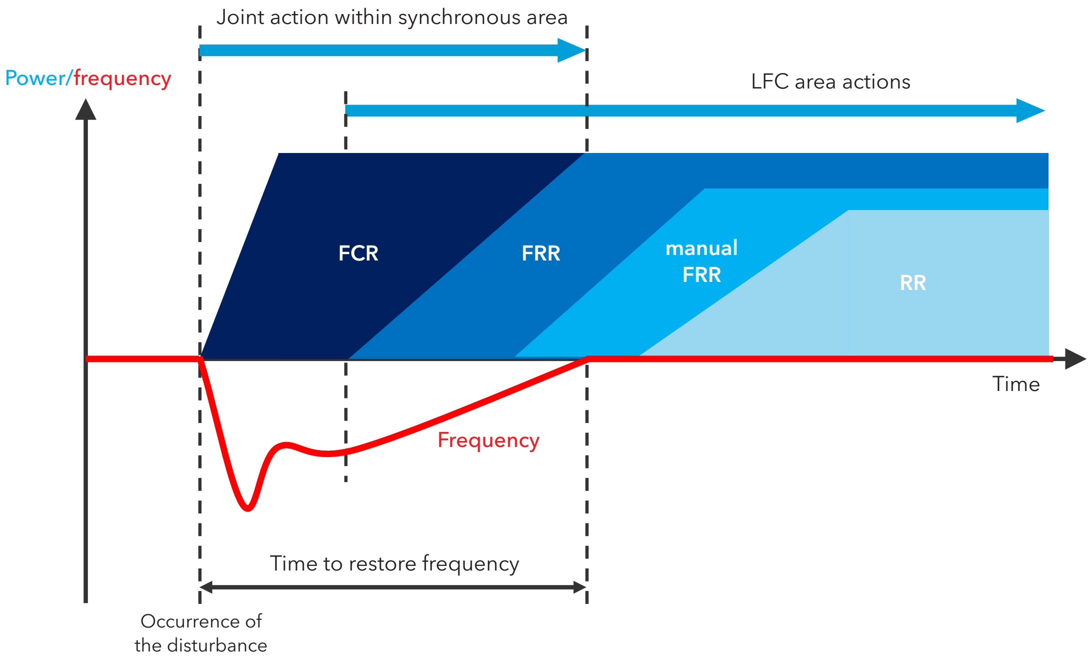


Figure 4 - Dynamic hierarchy of Load-Frequency Control (LFC) processes in Europe's ENTSO-E region [1]

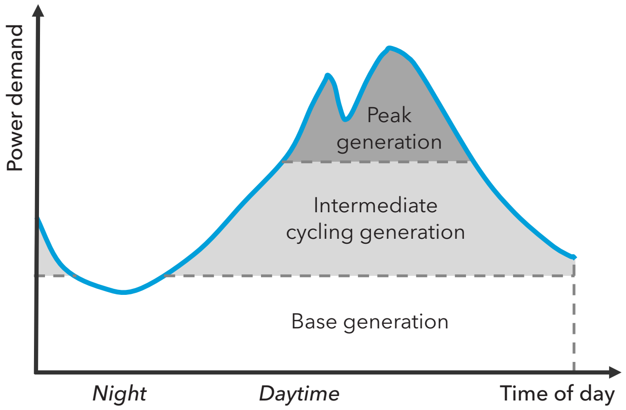


Figure 5 - Matching types of generation with demand during a day

Historically, variability and uncertainty in the system mainly occurred on the demand side (and due to failures), see figure 6. This variability was to be matched top down through flexibility services, predominantly provided by fast-ramping conventional power generation plants. To ensure this flexibility is provided at the right location in the grid at the right time, sufficient and reliable network interconnections are needed. Other flexibility services can be provided by consumers that offer to disconnect or reduce consumption, i.e. demand side management.

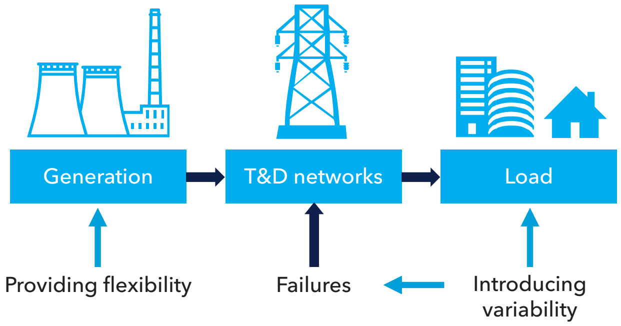


Figure 6 - Conventional sources of variability and flexibility in the power system

FUTURE ENERGY SYSTEM DEVELOPMENTS

The electricity system, including technical infrastructure and operational platforms, needs to continuously develop to account for developments in demand (e.g. electric vehicle charging), generation (e.g. distributed generation) and regulations (e.g. sustainability goals). Important considerations in future system development, as depicted in DNV GL's Energy Transition Outlook 2017 [2], are generation fuel mix (including RES and decentralisation of generation), energy generation technologies, network interconnectivity, technological innovations (including smart grid and ICT) and developments at the demand side. System requirements and regulations are key elements that affect the short, medium and long-term development of the electricity supply system. Uncertainties in requirements and regulatory pathways introduce challenges for the system and a need for flexibility services.

Historically, reliability and cost considerations were the main drivers to develop the electricity system. Since a couple of decades, however, sustainability is increasingly becoming a dominating factor that currently starts to have an impact on how the electricity system operates, as national and international regulations, including targets to deal with global warming, need to be taken into account. Energy systems are facing challenges to enable an energy transition in line with the latest international agreements on the climate and the environment, such as the UN Paris Agreement [3]. These agreements determine ambitious targets for renewable energy integration, efficiency increase and CO_2 emission reduction. Targets are implemented on regional and national levels by, amongst others, renewable energy support mechanisms, energy efficiency measures, and cogeneration (power and heat) and trigeneration (power, heat and cold) initiatives. Such regulations significantly influence the decisions for electricity system development taken in the short term to achieve the pre-set targets in the medium and long term. The 'energy trilemma' thus needs to be considered when providing consumers with energy, because it should not only be affordable and reliable, but also sustainable (figure 7).

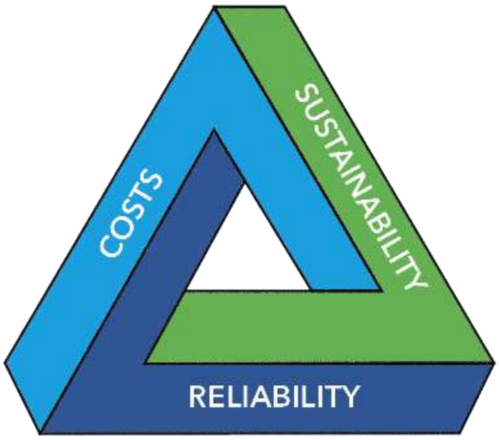


Figure 7 - The energy trilemma

There are worldwide challenges related to replacing and upgrading ageing technical infrastructure, often coupled with the challenge of adapting the system to the sustainability ambitions. This can, for example, lead to shutting down and mothballing existing generation units in favour of new ones. On the other hand, system upgrades provide opportunities to include novel generation units, such as RES, and to extend consumer participation through distributed generation units.

The major trends requiring adaptations in infrastructure and operation of the electricity system (see also DNV GL's Energy Transition Outlook [2]) are the expected increase of:

- renewable energy sources (RES): Environmental targets are expected to become more and more stringent, resulting in an increasing uptake of RES units. Increased levels of RES generation (figure 8) are common to most future energy system scenarios that commit to international environmental targets for 2020 and beyond. This increased uptake is already taking place today due to drastically decreasing costs of RES plants (figure 9) and this is expected to continue to decrease. This trend is expected to introduce unpredictability and variability at the generation side in the network, which requires flexibility at other levels in the system.
- network interconnectivity at the continental level: interconnections are mainly used to connect remote large RES plants with a broad consumer base. For example, China is developing a vast HVDC program to connect power resources in the west to the populated areas in the east (figure 10) [4]. Furthermore, in New Mexico, USA, the Tres Amigas project [5] will enable the connection of USA's existing three primary interconnections while integrating substantial renewable energy sources. And the EU promotes supranational interconnections in its internal energy market regulations [6]. Interconnections over large distances can be achieved through, for example, HVDC connections and hybrid AC/DC grids [7].
- dynamic behaviour at the distribution level and consumer side, as well as changing demand trends [8]:
  - the increasing participation of end-consumers (previously predominantly passive) through distributed energy resources, thereby becoming prosumers (i.e. producers & consumers)

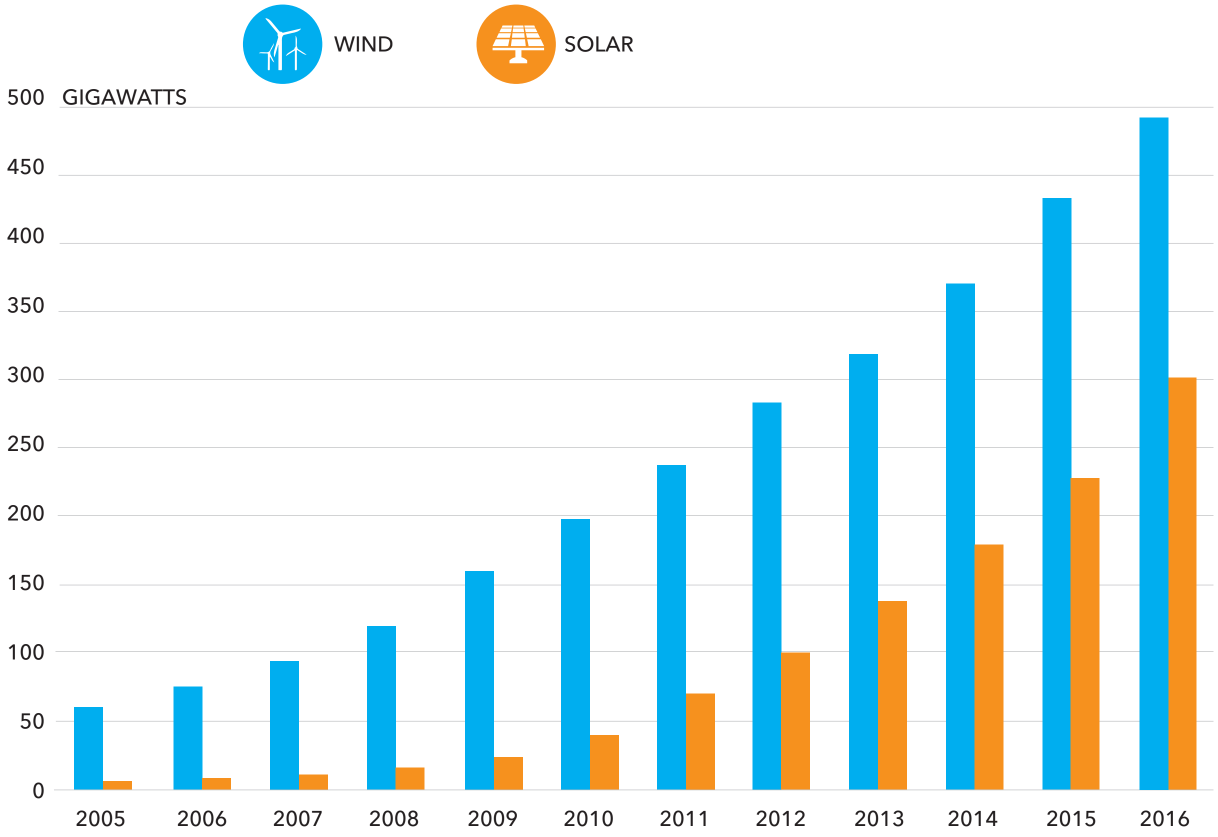
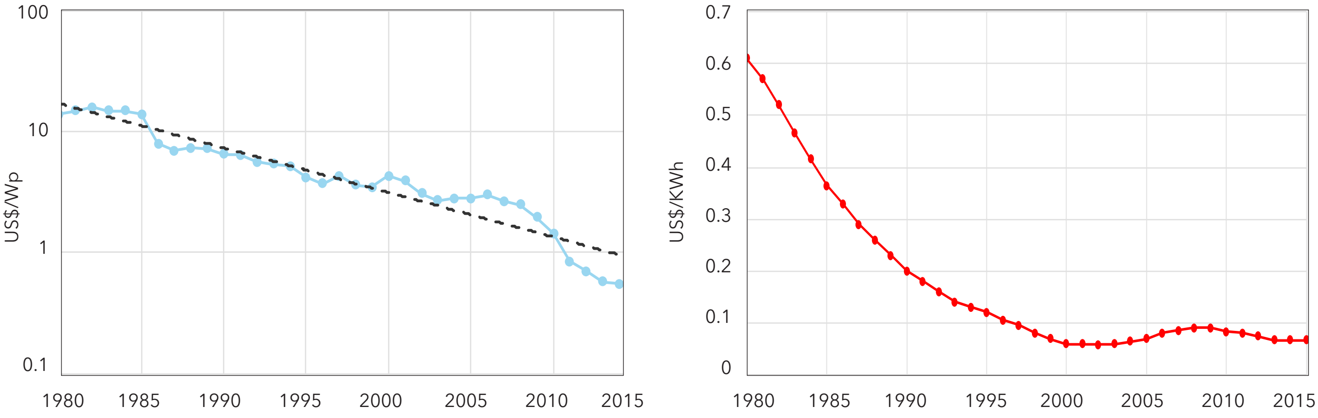


Figure 8 - Global total installed wind and solar power capacity



a) b)

Figure 9 - Costs of wind energy and solar power have drastically decreased over the last decades: a) solar PV cost of installed power; b) land-based wind energy cost per kWh (USA)

- the uptake of electric vehicles, smart appliances and energy storage, coupled with smart meters and (real-time) consumption and appliance monitoring
- the increased uptake of heat and power cogeneration to make use of waste heat from electricity generation processes, thereby increasing overall energy conversion efficiency
- the development of microgrids and smart grids, combining distributed energy resources in a clustered area of consumers with smart appliances, controller technology and local market operation, for local balancing of supply and demand
- the electrification of heating and cooling
- power to anything (P2X) products and services, like power to gas (P2G)

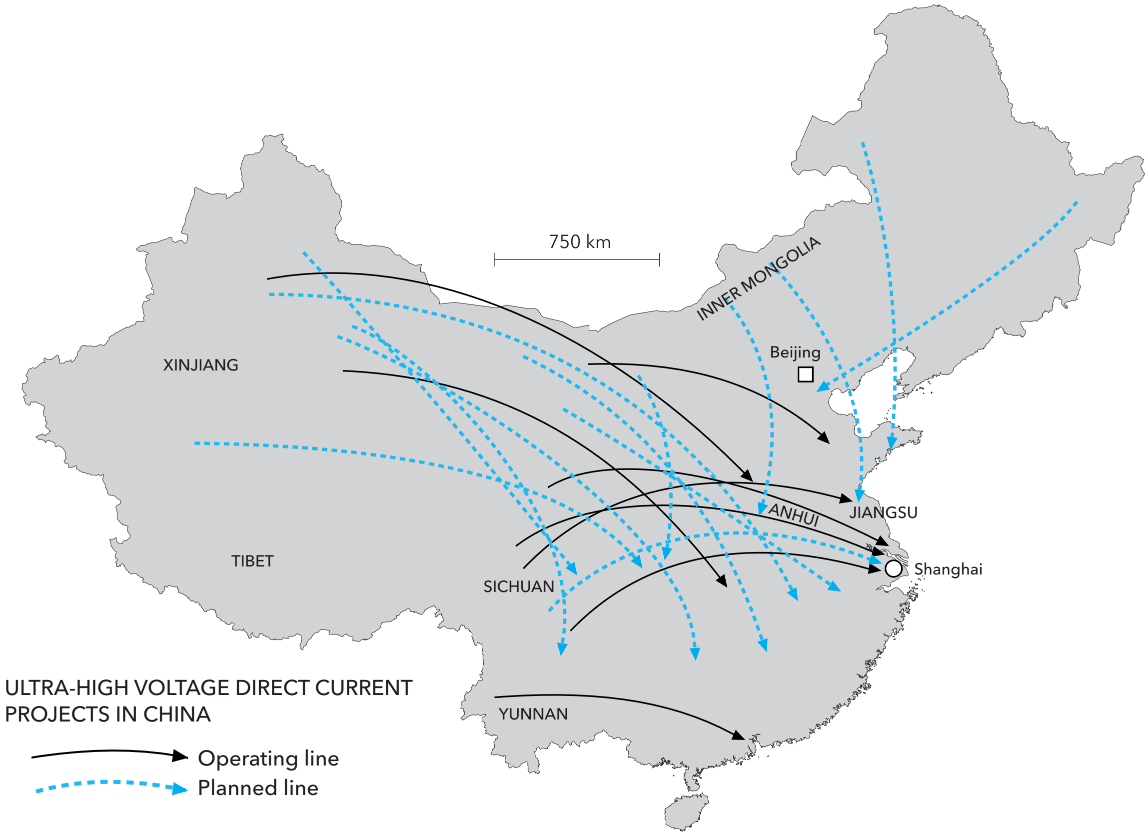


Figure 10 - China's HVDC interconnections

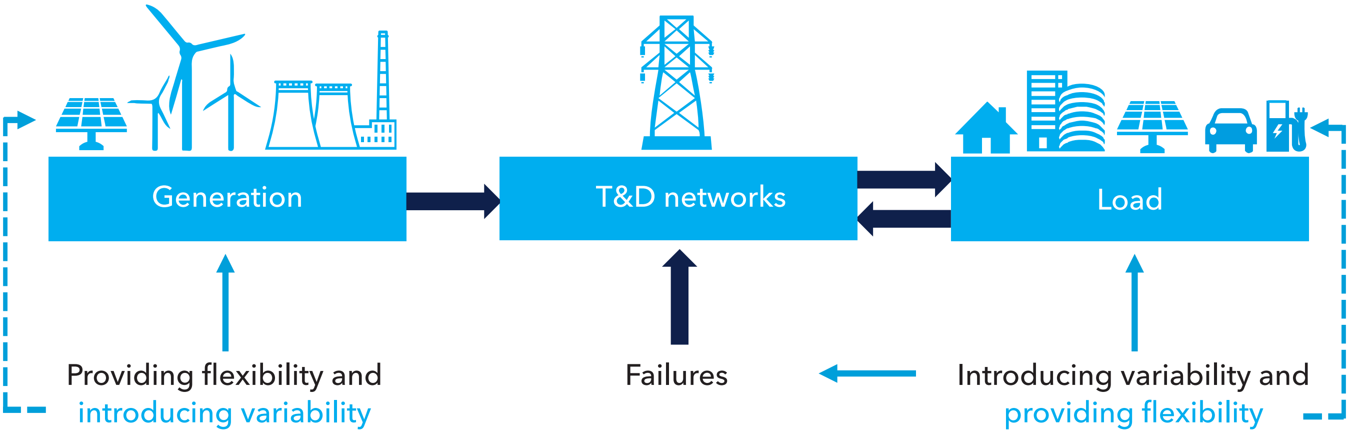


Figure 11 - Sources of variability and flexibility in future power systems

DEMAND-SIDE FLEXIBILITY: POWER-TO-ANYTHING PRODUCTION

A large source of industrial demand-side flexibility is present in existing and new production processes with electric power input, like production of heat (P2H – power to heat), hydrogen gas (P2G – P to gas), or other products (P2P – P to products, P2L – P to liquids). In a general term this is called power to anything: P2X. The common concept is that storage is on the X side, not on the electrical side, and that the electric power input does not need to be constant, but may vary according to requirements from the network or supply/generation side, without jeopardising the production process downstream.

P2G, for example, can be used to produce hydrogen as possible transportation fuel. P2G and P2L are particularly interesting due to their potential for long-term storage, to overcome weekly and even seasonal variability. Alternatively, P2H can be used for heating networks with heat storage.

More information on P2G can be found in the white paper "Power-to-Gas in a decarbonized European energy system based on renewable energy sources" of the European Power to Gas Platform [9].

Significant levels of variable RES, interconnectivity and end-consumer participation are thus expected to change the structure and operation of power systems (figure 11). The technologies and developments enabling more active and dynamic consumer behaviour can also provide flexibility services to the system. This is in contrast with the passive, rigid consumer demand behaviour of the near past. On the other hand, variability will also increasingly occur at the generation side due to variable RES.

WHY IS FLEXIBILITY NEEDED?

Flexibility is needed in the power system to compensate for variability of any kind, to maintain balance between electricity demand and generation. The previous section shows that the number of sources of variability is increasing, and therefore the need for flexibility is also increasing. Looking at power generation: if the share of power generated by variable renewable sources (i.e. wind and solar) increases to a high level, e.g. 50%, additional generating capacity in the form of conventional, dispatchable units may be needed for flexibility to compensate for the RES variability. Based on this assumption, the generating cost of electricity (per kWh) goes up, although the generating cost of renewables is lower than the generating cost of fossil-based electricity. However, studies show that the balancing costs are actually going down because of other factors (figure 13).

The increased need for flexible dispatchable generation capacity is illustrated by looking at the residual load (this is the power demand minus the renewable energy generation) at, for example, a national aggregated level. The variability of this residual load is expected to increase due to the increased variability of both the demand and the RES generation. Peak variability in the system is expected to increase, as illustrated in figure 12. In addition, available electricity generated by RES might exceed demand during hours with low demand. Therefore, RES may need to be curtailed to maintain system balance. Curtailment, however, meets societal objections and will challenge cost-effectiveness of electricity supply.

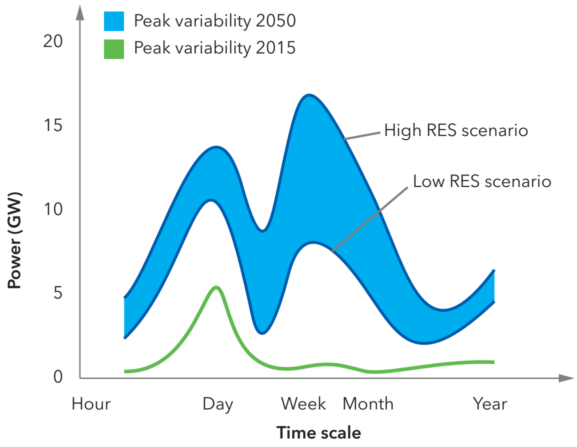


Figure 12 - Peak power variability at different time scales in the Dutch electricity grid in 2015 and expected in 2050

Regarding demand side variability, the increase in electricity demand, peak power demand and demand variability also asks for an increase in power system flexibility. The peak power demand is conventionally matched by fossil-fuelled ‘peaking’ power plants that can react quickly, but have a low utilisation rate, because the peak only lasts for a few hours a day (and does not occur each day).
Other sources of flexibility, for example on the demand side or energy storage, may be favourable. The increase in peak power demand and demand variability might also increase the strain on network infrastructure. Moreover, local grid congestion may occur because of peaks in demand or in distributed generation. Therefore, also flexibility solutions for grid load management are needed.

FUTURE NEED FOR FLEXIBILITY: EXPECTATIONS VERSUS REALITY

Is more flexibility needed because of the increase in RES? And should this flexibility be in the form of generation reserves for balancing? To illustrate the uncertainty around this topic: figure 13 shows two developments in the period from 2008 to 2014 for the German market: one is the increase in wind and solar generation capacity by almost a factor of three and the other is a *decrease* in the need for balancing reserves and balancing costs. Note that these are influenced by factors such as cross-border balancing and netting [10] and electricity market developments in general. It shows that for this period in Germany, there is no clear relation between the increase in RES capacity and the development in the balancing reserve.

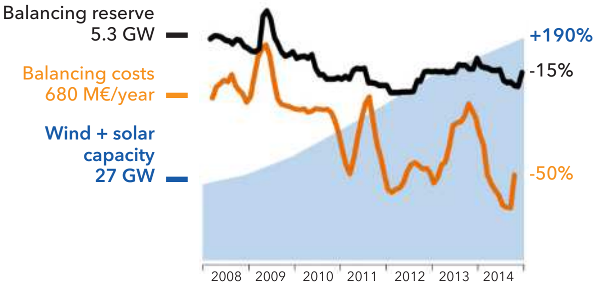


Figure 13 - Balancing reserve development in Germany 2008-2014 [11]
Numbers on the left axis are 2008 values

HOW TO PROVIDE FLEXIBILITY?

INTRODUCTION

Traditionally, flexibility was mainly provided by (fast reacting) conventional power plants (e.g. gas turbines). However, flexibility can also be provided by other resources (figure 14), each with their own techno-economic characteristics:

(1) flexible conventional generation (business as usual)
(2) flexible demand (DSM/DR)
(3) increased (inter)national grid interconnectivity,
(4) energy storage
(5) RES curtailment

Flexibility services can thus not only be provided at the supply side in the network, but also at the demand side and through improved electricity transport, see figure 15. Novel technologies at the consumer side, such as electric heat pumps and electric vehicles, can provide flexibility services that combine characteristics of both demand response and storage.

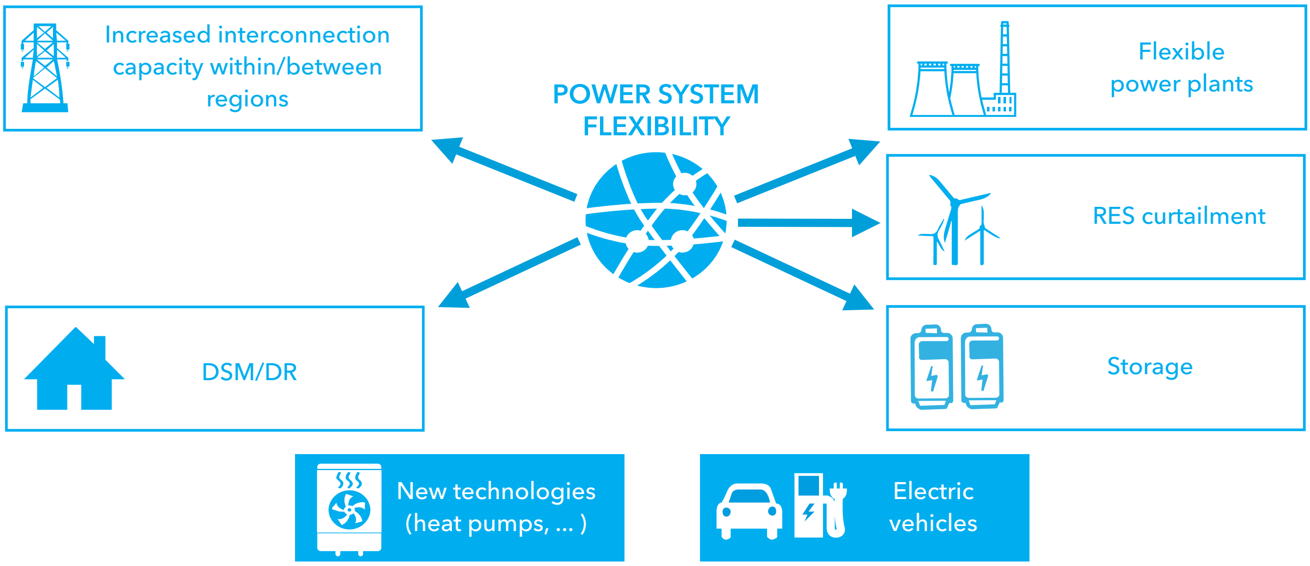


Figure 14 - Flexibility options in the power system

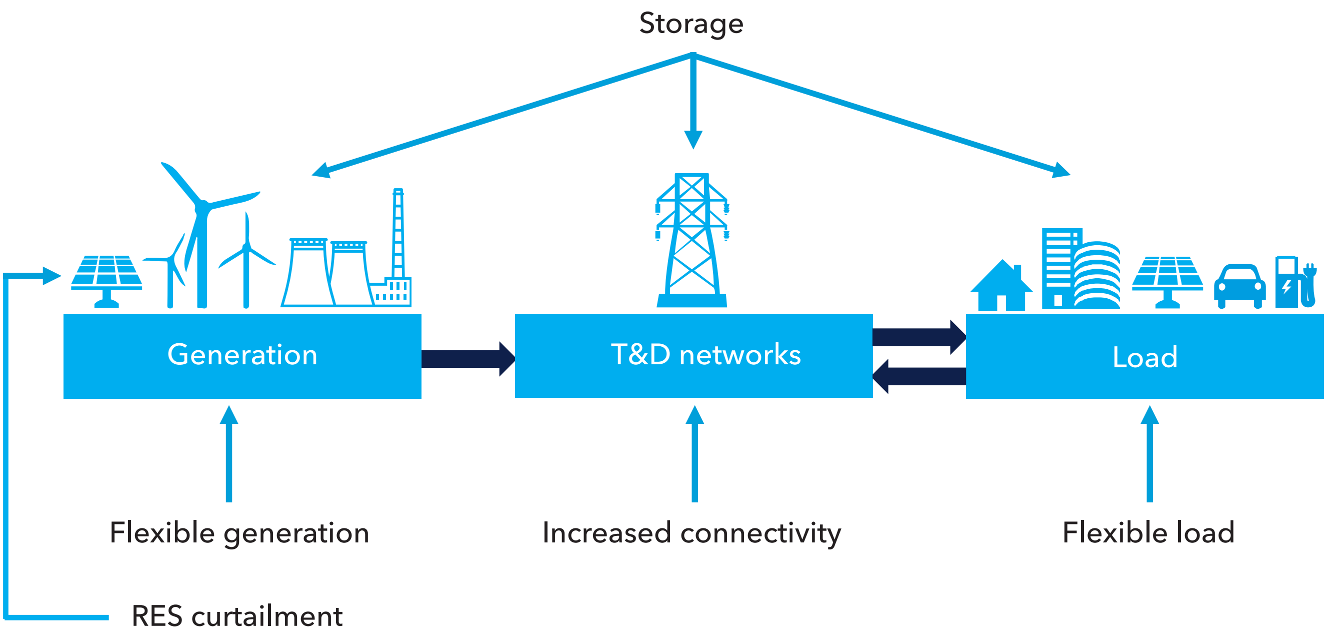


Figure 15 - Flexibility sources in the electricity supply system

Flexibility incorporates a range of services, that attend to different flexibility-related purposes, see table 1 on page 16. In this table, also the possible resources are mentioned.

TIME AND PLACE OF FLEXIBILITY

To deal with variability in the system, flexibility at different levels in the network and at different operational time scales is required. Different types of flexibility serve different purposes and have different technical and market-based characteristics, see also in the next section.

Time scale
Variability in the electrical system occurs at different time scales, see figure 16. For example, where solar energy varies with the day and night rhythm, wind energy is more influenced by slowly moving low pressure areas (at a time scale of multiple days). Furthermore, solar and wind energy show variability on the hourly and shorter time scales (minutes down to sub seconds), due to wind variations, wind gusts and cloud coverage. On the other hand, flexibility services each have their operational timescales (e.g. start-up time of a gas turbine or discharging time of an energy storage device) and need to be matched with the flexibility required in the system.

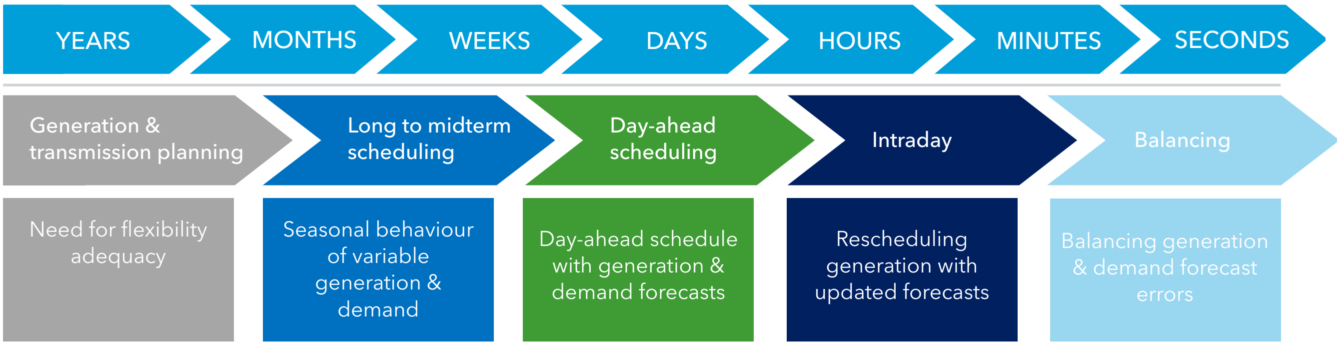


Figure 16 - Timescales where flexibility is needed and nature of the flexibility required

SERVICE	RESOURCES
Bulk (generation) energy services	
1. Electrical energy time-shift (e.g. prevent RES curtailment)	Demand side management (DSM), energy storage, grid extension
2. Power supply capacity (prevent generation overload)	Flexible generation, energy storage, grid extension
Ancillary services	
3. Load following	Flexible generation, energy storage
4. Regulation (power balancing)	Flexible generation, energy storage, DSM
5. Frequency response	Flexible generation, energy storage, DSM
6. Spinning, non-spinning and supplemental reserve	Flexible generation, energy storage, DSM
7. Voltage support	Flexible generation, energy storage, DSM
8. Black start	Flexible generation, energy storage
Transmission infrastructure services	
9. Transmission congestion relief	Energy storage, DSM, RES curtailment, grid extension
10. Transmission upgrade deferral	Energy storage, DSM, RES curtailment
Distribution infrastructure services	
11. Distribution upgrade deferral	Energy storage, DSM, RES curtailment
Customer energy management and microgrid services	
12. Power quality	Flexible generation, energy storage
13. Power reliability (grid-connected)	Flexible generation, energy storage, RES curtailment, grid reconfiguration
14. Power reliability (microgrid operation)	Flexible generation, energy storage, RES curtailment, grid reconfiguration
15. Retail electrical energy time-shift	Energy storage, DSM
16. Demand charge management	Energy storage, DSM
17. Renewable power consumption maximisation	Energy storage, DSM
Renewables integration	
18. Ramp rate control	Energy storage
19. Generation peak shaving	Energy storage, DSM, grid extension
20. Capacity firming	Energy storage

Table 1 - Applications of flexibility, in six umbrella groups (adapted from [12])

Short-term flexibility (provided from a few (sub)seconds to about 15 minutes) is required for real-time balancing operation. Medium-term flexibility (from an hour to a few hours up to a day) is required in the intra-day and day-ahead markets to (re)schedule generation to supply the predicted demand, or to (re)schedule flexible demand to adapt to predicted variable RES. Last, long-term flexibility services are contracted weeks, months and even years ahead to anticipate long-term developments. The latter relates, for example, to hydro-electric reservoir storage or commissioning of new power plants.

Other technical properties interlinked with time scale are the response time of a system after a flexibility request, the ramp rate to full output power, the maximum duration of the flexibility resource (e.g. before recharging is needed), and the acceptable time range of energy shifting (e.g. with demand response).

Location in the power system

The location of both the occurring power variations and the flexibility resource will determine the potential of the resource to manage the variations. Conventional generation units are connected at the high voltage level, whereas renewable generation can be connected at the high, medium and low voltage levels (distributed generation). Due to geographical constraints of the availability of renewable energy, renewable energy inflows at certain points in the network might cause network congestions. Similarly, local demand peaks can give rise to local network overloading.

The appropriate location of available flexibility services is therefore important to relieve geographical specific issues in the system (figure 17).

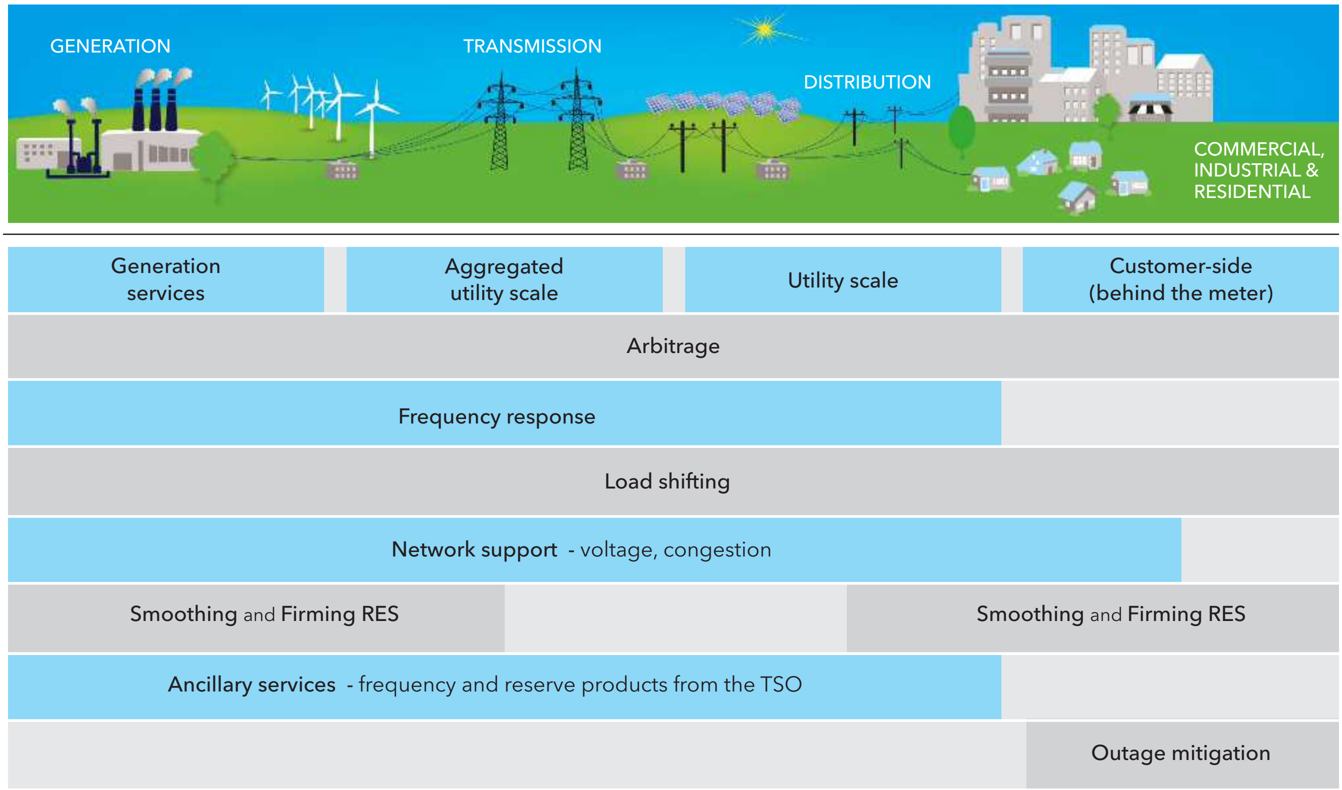


Figure 17 - Map of different flexibility services at different network locations

COSTS AND BENEFITS OF FLEXIBILITY

Apart from technical characteristics of flexibility resources, also their operational strategies and business cases determine their suitability and investment interest. The business case is determined by the costs of the resources and the revenues they can generate over their lifetime.

The costs of the resources are generally given in terms of investment cost intensity (€/kW) and the cost of providing flexibility, i.e. variable operation and maintenance charge (€/MWh) and fixed operation and maintenance charge (€/MW/yr). Additionally, the unit's technical lifetime will determine return on investment.

The choice for a flexibility service or a combination of services will determine potential revenues. Ownership models and regulatory frameworks may restrict the potential services (e.g. whether the services are market based or not) and their revenues.

The business case analysis of a flexibility resource can focus on the total value to society by comparing cost and benefits, and/or on the financial business case for the party owning and operating the flexibility resource.

For most flexibility resources, providing a single flexibility service will not ensure a positive business case. Stackable revenues, by combining operational services in different markets and time scales, will therefore become important to render the business case of flexibility resources worthwhile. Different streams of income can, for example, come from providing energy supply, balancing services and network services. The StRe@M model, developed by DNV GL, is able to capture and determine the stackable revenues of different services provided by a single flexibility resource. This is further illustrated in the final chapter through specific case-studies.

ECONOMIC MARKET: MARKET DESIGN FOR HETEROGENOUS FLEXIBILITY PRODUCTS

A market design for heterogenous flexibility products addresses two issues: incentives for investments in flexible balancing capacity and incentives for specific locations of generation and demand.
Through a system of imbalance penalties and compensation, market participants are encouraged to optimally maintain their demand-supply balance. However, since the balancing market is not transparent, market parties are inclined to minimise their *own* imbalance in their operations, without making specific investments to provide flexibility *for others*. And currently, only the TSO is responsible for purchasing balancing capacity (i.e. a single-buyer market). Alternatively, the responsibility for reserving spare capacity for balancing could be placed with the market participants. This can be facilitated by a two-sided balancing market where market participants (e.g. a wind operator) can purchase flexible balancing capacity from another market participant (e.g. with a gas-fired power plant). Such a platform would connect the demand for flexibility with the flexibility providers, incentivising market participants to invest in flexibility capacity not just for their own purpose.
Secondly, there is no market-based incentive for locating a generation asset at a particular grid connection point within a bidding zone/country. Moreover, the grid company has the legal duty to connect an asset to the grid, irrespective of the location. In the future, this can increase grid congestion and negatively affect the grid stability. A new market could provide an incentive for siting the asset such that it reduces grid congestion. An example is to have a *local* -balancing product by adding locality information to the balancing offers on the two-sided balancing market. DSOs can purchase the required flexible capacity from this balancing market by selecting the offers with the relevant location information. This would especially create opportunities for local storage and smart grids.

(Based on: DNV GL, Exciting times for the Dutch grid – Creating a healthy electricity market for a new energy landscape)

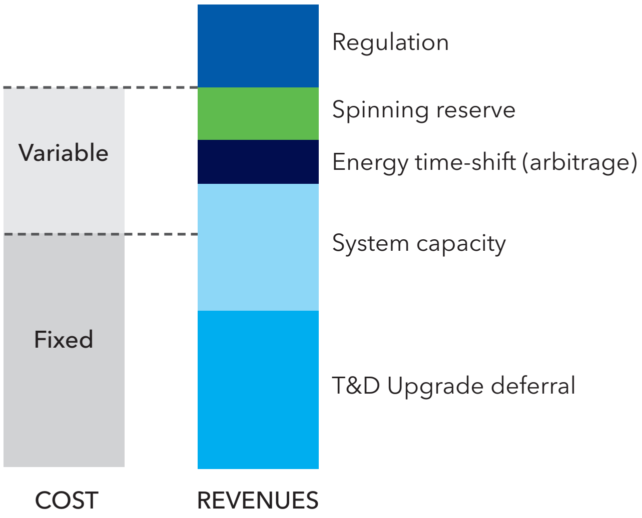


Figure 18 - Principle of stackable revenues by providing different services simultaneously to offset total cost

FLEXIBILITY RESOURCES

Flexibility in conventional generation

Flexibility provided by conventional generation units means providing additional electrical energy to the system (increase generation), or withdrawing energy from it (decrease generation), when required. Flexible conventional generation is historically the main source of flexibility in the system.

Base generators, e.g. nuclear and coal-fired power plants, are most economic to operate (i.e. have the lowest marginal costs), but are relatively costly to start and stop or run at low loading. Hence they are preferably continuously operated at maximum power to cover base load. Other units, such as gas turbines, are costlier to operate, but have short start and stop times and fast ramping rates. The latter units are thus preferably engaged to cover peak demand events of a few hours.

Improving the flexibility of existing generators can help to deal with high levels of variable renewable energy inflow and increased peak demand events in the system. This can be improved by increasing ramp rates and decreasing start and stop times of the generators, thereby negating the need for additional, expensive peak power generators.

In the past years, several characteristics of conventional power plants are already being improved. One of these is the ability to work at low minimum loading levels: traditional fossil-fuelled and nuclear power plants cannot run in stable operation below a loading of half their nominal power capacity, but some modern fossil-fuelled plants can operate at loading levels down to 20%. Table 2 summarises average, state of the art and optimisation potential of technical characteristics of conventional power plants. This overview shows that significant flexibility improvements are foreseen in modernised versions of conventional generation resources.

With increasing penetration levels of variable RES, conventional generation units will more often operate at part load (when RES output is high), or only at limited periods of time throughout the year (when RES output is very low), meaning that they have a low utilisation rate, thereby reducing their (economic) efficiency.

	PLANT TYPE	Hard coal	Lignite	CCGT	OCGT
Ramp rate	$\%P_n$/minute	1.5 / **4** / 6	1 / **2.5** / 4	2 / **4** / 8	8 / **12** / 15
Within power range	$\%P_n$	40 - 90	50 - 90	40* - 90	40* - 90
Minimum load	$\%P_n$	40 / **25** / 20	60 / **50** / 40	50 / **40** / 30*	50 / **40** / 20*
Start time: hot (<8h)	h	3 / **2.5** / 2	6 / **4** / 2	1.5 / **1** / 0.5	<0.1
Start time: cold (<48h)	h	10 / **5** / 4	10 / **8** / 6	4 / **3** / 2	<0.1

* based on NOx and CO limits

Table 2 - Flexibility properties of conventional generation units: figures are given for {the present/state-of-the-art/optimisation potential} [13]

In some cases (e.g. in the UK) this has required the introduction of a 'capacity market' in order to pay such generators for their stand-by capacity (separately from their energy production). Otherwise some of these generators would close down, which would result in insufficient power capacity at peak consumption on rare occasions.

Furthermore, conventional generation units, especially the ones providing primary reserves, operate on fossil fuels, leading to issues related to the emission of greenhouse gasses. This makes flexible generation not ideal for future flexibility under long-term climate agreements.

Flexible demand

The second flexibility option focusses on the demand-side, rather than the supply side. Flexible demand controlled by the utility or retailer is called demand side management (DSM); when it is controlled by (or on behalf of) the consumer himself, it is referred to as demand response (DR). Demand side actions have the goal to reduce (or increase) consumption in a certain period, which often means shifting consumption from that period to another. In most cases, the end consumer will receive compensation payments for this.

DSM refers to the utility or retailer influencing actions at the end consumer level to adapt demand during specific times. DSM is mainly applied to industrial and commercial customers. In a broader sense, DSM also includes efficiency measures and demand changes, controlled or recommended by the utility or retailer. DR is similar to DSM but refers to conscious actions undertaken by end consumers to adapt their demand in reaction to incentives. Generally, both terms are used interchangeably, but, according to the definitions above, DR is started each time by the end consumer (mostly automatically, but could also be manually) and DSM is started by the utility at times previously agreed in a framework contract. Demand-side initiatives theoretically have a high potential, i.e. the entire demand side of the system could be used to provide demand flexibility, as depicted in figure 19. This could be a more cost-effective way to provide flexibility compared to flexible conventional generation. However, of this theoretical potential, only available controllable loads with the right technological capability can be used for demand flexibility. Technological potential is also bound through operational and technical limitations (including available power, speed of response, …).

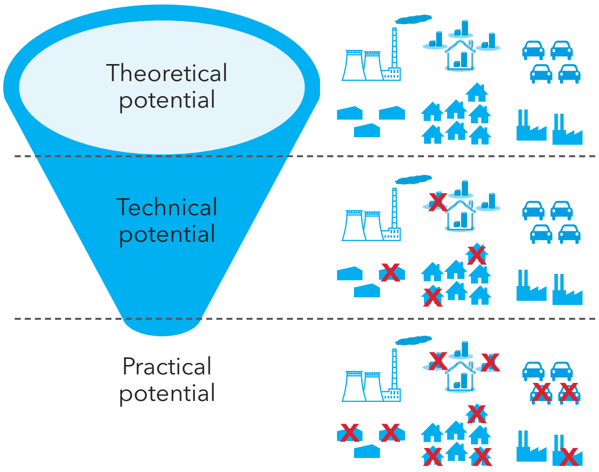


Figure 19 - Illustration of the potential of demand-side flexibility

Managing flexible demand has already been implemented worldwide and it serves as balancing product in the operational platforms of electricity supply systems in many countries. A straightforward approach of DR is using time-based electricity tariffs, e.g. day (higher) and night (lower) tariffs, peak and valley tariffs, or summer and winter tariffs. In this approach, consumers are encouraged to reduce consumption during high tariff periods, but it is not enforced, so the result may vary.

Demand flexibility can also be implemented in reserve markets through tendered contracts between utilities, TSOs or DNOs and end consumers, mostly industry. For example, in EU countries this is done in bilateral contracts (OTC), or in a single buyer market, where parties can offer flexibility capacity to the TSO in different imbalance markets at different timeframes at a certain price. Parties that can offer this demand flexibility are mostly industrial companies, such as greenhouse owners or companies that have daily pumping requirements. These parties have a certain electricity demand, but the exact time in the day (or week) of this demand could be changed according to flexibility requirements in the market without disturbing the company's primary processes. Alternatively, instead of using a single-buyer market, demand-side flexibility can be organised through regulated plans for disconnection in case of shortages in generation capacity. An example of this is the Belgian national disconnection plan that was put in place in 2005, and can be activated automatically in case of high voltage network disruptions, or manually in case of insufficiency of available generation capacity [14].

DSM and DR can be used to control demand profiles in various ways, such as peak shaving (to reduce peak load on the system), or increasing demand (e.g. to help with frequency control or to absorb local RES surplus energy). Fast demand-side flexibility (e.g. frequency response) at the residential level could be provided through smart meters and smart energy boxes/controllers that control electric household appliances (like electric heat pumps, air conditioning units, smart freezers, or electric vehicle charging) [8].

At an industry level, decreasing or switching off non-time-critical processes could provide demand-based flexibility. Examples are industrial freezers, short-time batch processes, municipal water pumping and waste water treatment. A large source of industrial demand-side flexibility is the power-to-X production mentioned before.
Additionally, local microgrids or smart grids could provide larger, aggregated demand-side flexibility from a cluster of end consumers (homes, small industries and businesses). Within these future systems sophisticated communication and controls could be integrated to coordinate flexible resources across consumer-based supply and demand, both for local purposes and as a service to the central level.

A technical constraint of demand-side flexibility is the fact that it is generally limited to periods of a few hours. Furthermore, the effectiveness of price and incentives-based DR may be unreliable due to consumer behaviour; therefore, it is preferred to have automatic DR or DSM systems. On the economic side, the compensations and incentives provided to flexible end consumers introduce additional system costs. Furthermore, the large-scale and aggregated use of demand response will ask for development of and investments in sensors, controls, communications and IT infrastructure. This all makes the business case for demand-side flexibility often complicated and uncertain.
The Universal Smart Energy Framework, USEF, is established to reduce this complexity and uncertainty. USEF is a platform for market models for the trading and commoditisation of energy flexibility, and the architecture, tools and rules to make them work effectively.

USEF

USEF - AN INTEGRAL MARKET DESIGN FOR THE TRADING OF FLEXIBLE ENERGY USE

USEF, the Universal Smart Energy Framework, delivers one common standard on which to build all smart energy products and services. It unlocks the value of flexible energy use by making it a tradeable commodity and by delivering the market structure and associated rules and tools required to make it work effectively.
USEF fits on top of existing energy market models, and enables the integration of new energy markets. It is designed to offer fair market access and benefits to all stakeholders and is accessible to anyone internationally.
https://www.usef.energy

Other initiatives on smart energy communities and demand-side flexibility are research projects like VIMSEN **(http://ict-vimsen.eu/)** and NobelGrid **(http://nobelgrid.eu/)**.

Energy storage

The third source of flexibility is electrical energy storage (EES). An EES system is a system that reversibly converts electrical energy into another form of energy, vice versa, and stores energy internally. There are five broad classes of EES according to the form of energy inside the storage medium: electrical, electrochemical, mechanical, chemical and thermal. There are technologies from each class already deployed in the grid and there are others at various stages of maturity. The main technologies applicable for grid-connected storage are shown in figure 20.

An example of chemical storage is hydrogen (e.g. in the combination of an electrolyser, hydrogen storage and a fuel cell). Examples of thermal storage are (hot) water, ice, molten salt and ceramics. Chemical storage and thermal storage are less suitable for electrical discharge back into the grid, because the round-trip efficiency is very low in these cases.
At this moment, it is more economic to directly utilise the hydrogen (or other chemicals) in the industry or transportation sector (P2G, P2L), and the heat in heating applications in industry or in the built environment (P2H). These technologies are thus still sources of flexibility (decrease production in times of low RES generation, increase production in times of high RES generation), but better considered demand flexibility (DSM/DR) instead of electrical energy

Hybrid energy storage systems combine different classes of EES into one system (e.g. a combination of flywheels and Li-ion batteries or supercapacitors with a redox flow battery). The aim of hybrid systems is to combine the strengths of the different storage technologies into an improved storage system for multi-purpose flexibility, such as combining a power-intensive short-duration technology with an energy-intensive long-duration technology.

The most characteristic property of EES systems is their limited storage buffer, which means that continuous discharge for power generation is not possible (in contrast with flexible generation). However, the discharge duration varies over the different technologies: pumped hydro-electric storage (PHS) and compressed air energy storage (CAES) may provide power during several days or weeks. Also, the period of storage varies: this is very long for PHS and CAES, and shorter for Li-ion batteries and flywheels due to self-discharge.

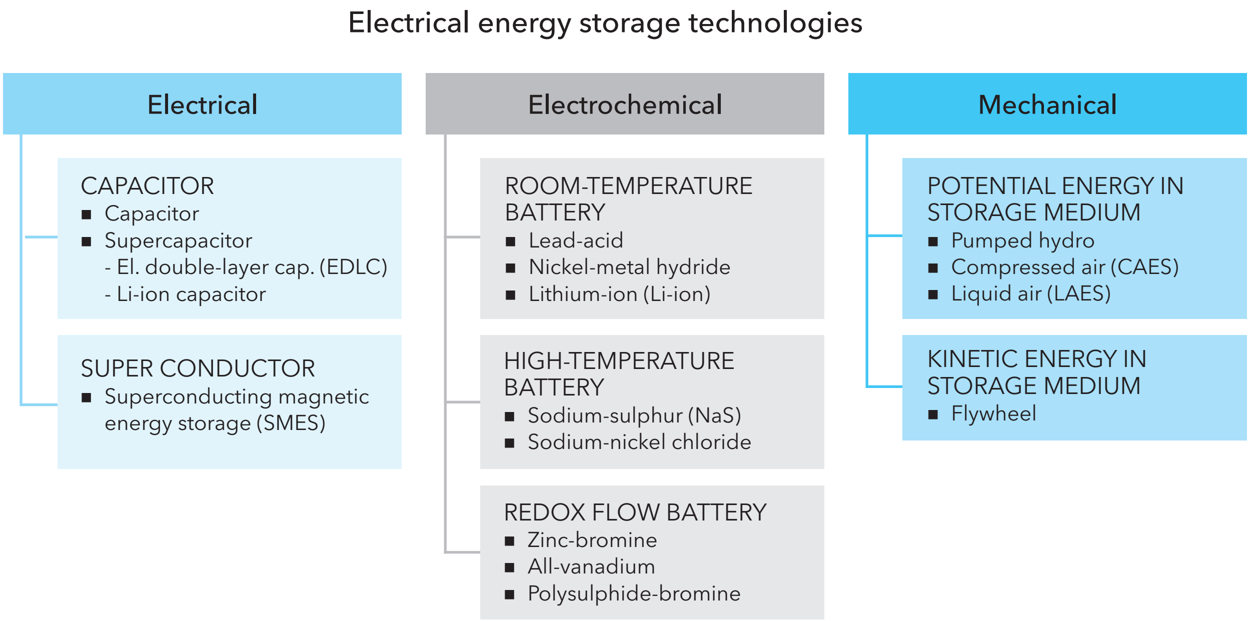


Figure 20 - Classification of main electrical energy storage (EES) technologies [12]

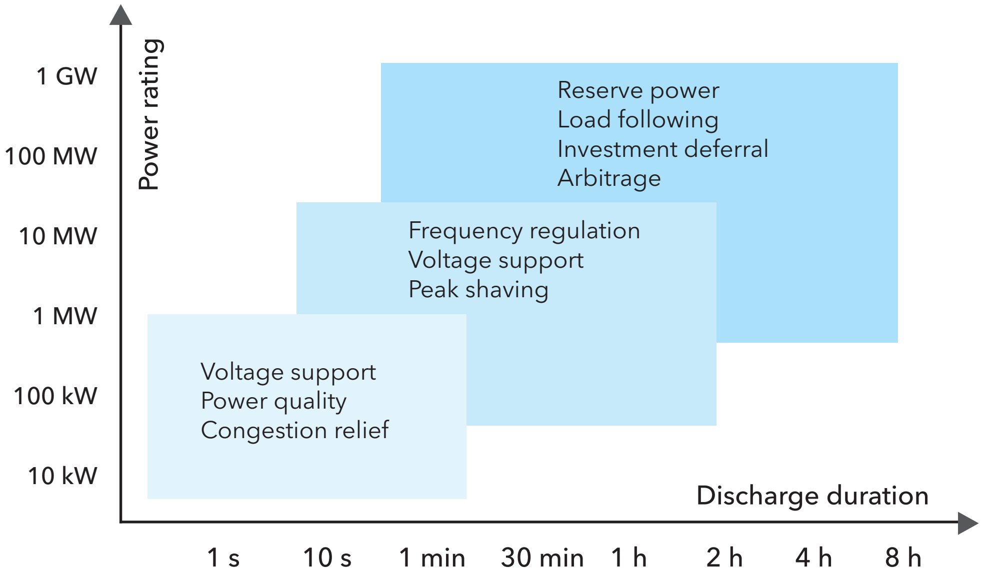


Figure 21 - Selected flexibility services with their discharge duration and power characteristics

Furthermore, EES systems have a very fast response and are easily scalable, ranging from small systems for local flexibility to large systems for central flexibility, including distributed systems (virtually large systems with many small units). They are also very flexible in controls and easily reconfigurable (e.g. for different flexibility services). Some EES technologies (like batteries) are fast to develop and install; this is an advantage compared to flexible generation or grid extension [8].

EES is more flexible than demand-side flexibility; however, EV charging and P2X have properties comparable to EES.

Because of the variety of energy storage technologies and the large range of storage system sizes, many flexibility services can be offered by energy storage systems. These can range from short duration and low power to long duration and high power, see figure 21 and figure 22.

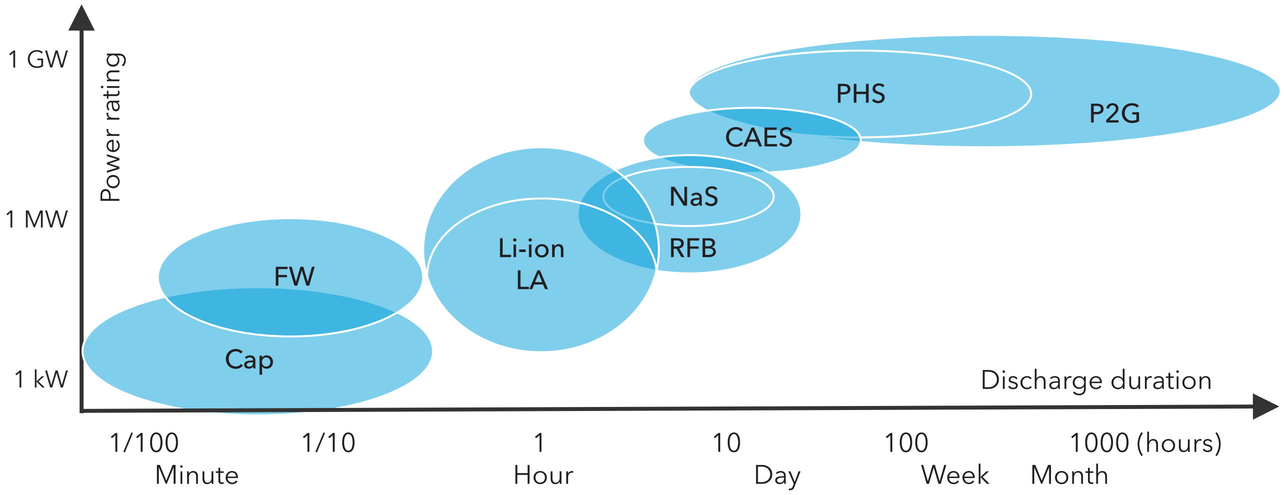


Figure 22 - Power versus discharge duration map of selected EES technologies

Depending on the technology, a certain form of grid integration will be most appropriate for an EES system. At the distribution level in the network, batteries are currently more prevailing. The cost of batteries is decreasing and they exist in various technologies with different application ranges. Li-ion batteries, for example, are suitable to provide ancillary services and can be installed both at the transmission and distribution level. Electric vehicles are another form of (moveable) batteries at the distribution grid level: they possess properties of EES and DR and could provide renewable energy absorption and grid congestion management services too. EES technologies with grid support applications in the sub-second range (e.g. power quality improvement) are flywheels and supercapacitors.

PHS is currently the only mature technology at the centralised transmission level. PHS systems are mainly used for energy time-shift services (with a fixed continuous power and a duration of hours), not for ancillary services (where variable power and short time frames are required). Li-ion batteries and redox flow batteries are entering the ancillary services markets.

On the down side, energy storage requires a conversion of electricity, leading to energy losses. Reconversion back to electricity will again incur energy losses. These losses are additional to the transportation losses of electricity from the generation source to the consumers. Therefore, the round-trip efficiency of an EES system is an important parameter in the selection of a system for a certain service. Energy storage also has practical limitations related to energy capacity and discharge duration, geographical conditions (PHS, CAES), stand-by losses (i.e. self-discharge, especially flywheels) and long-term storage duration (e.g. weeks or months and seasonal storage). Larger scale EES, in the order of GWh, is currently only achievable through PHS.

Energy storage is an additional device to the system, whereas flexible generation and DSM/DR are add-on services to existing equipment. This means that storage is relatively expensive in general.
EES systems are being used for several flexibility services. Because of their relatively high cost and their space requirements, their uptake is going in a slow to moderate pace.

Through combining services delivered by a single storage system, ‘stacked’ revenues (figure 18) will help to overcome the cost barrier and enable wider adoption of energy storage [15].

Additionally, the integration of EES is subject to technical standards. Standards are lagging the development and uptake of storage technologies and systems, which forms a barrier for these emerging technologies and new operational schemes in the current power system. Standardisation is especially relevant for storage units deployed in the neighbourhood of end consumers in the network. To fill the standardisation gap, DNV GL developed its GRIDSTOR document, a Recommended Practice on safety, operation and performance of grid-connected energy storage systems [12].

GRIDSTOR

The GRIDSTOR initiative was spurred by the realisation that the enery industry lacked a comprehensive framework covering all elements relevant for grid-connected energy storage systems.
The GRIDSTOR Recommended Practice (RP) has been launched in December 2015 and updated in September 2017.
This RP is a transparent and globally recognised recommended practice focusing on three main aspects of grid-connected energy storage: system safety, operation and performance.

Network reinforcement
The fourth source of flexibility concerns reinforcing and expanding transmission and distribution networks. Grid expansion was previously introduced to connect unpopulated areas of large-scale (renewable) generation with populated areas of high power demand. This can also be considered as adding flexibility: new cross-border interconnections could be installed at points without an existing connection or at existing points with congestion problems. Also within regional distribution networks, local flexibility solutions are required, that can be provided through meshed distribution, dynamic rating and/or additional medium and low voltage connections.

In Europe, the synchronised areas can be further expanded towards a fully interconnected system, i.e. a supergrid, as illustrated in figure 23.
All available large-scale renewable energy resources could in this way be exploited and balanced over the whole continent. Research projects on this topic are NorthSeaGrid [16] and PROMOTioN [17].

Other developments in grid flexibility include dynamic reactive control mechanisms that can deal with rapid changes in the loading of transmission lines. Also, power flow control is being developed to allow grid operators to better direct and balance power flows over a broader network.

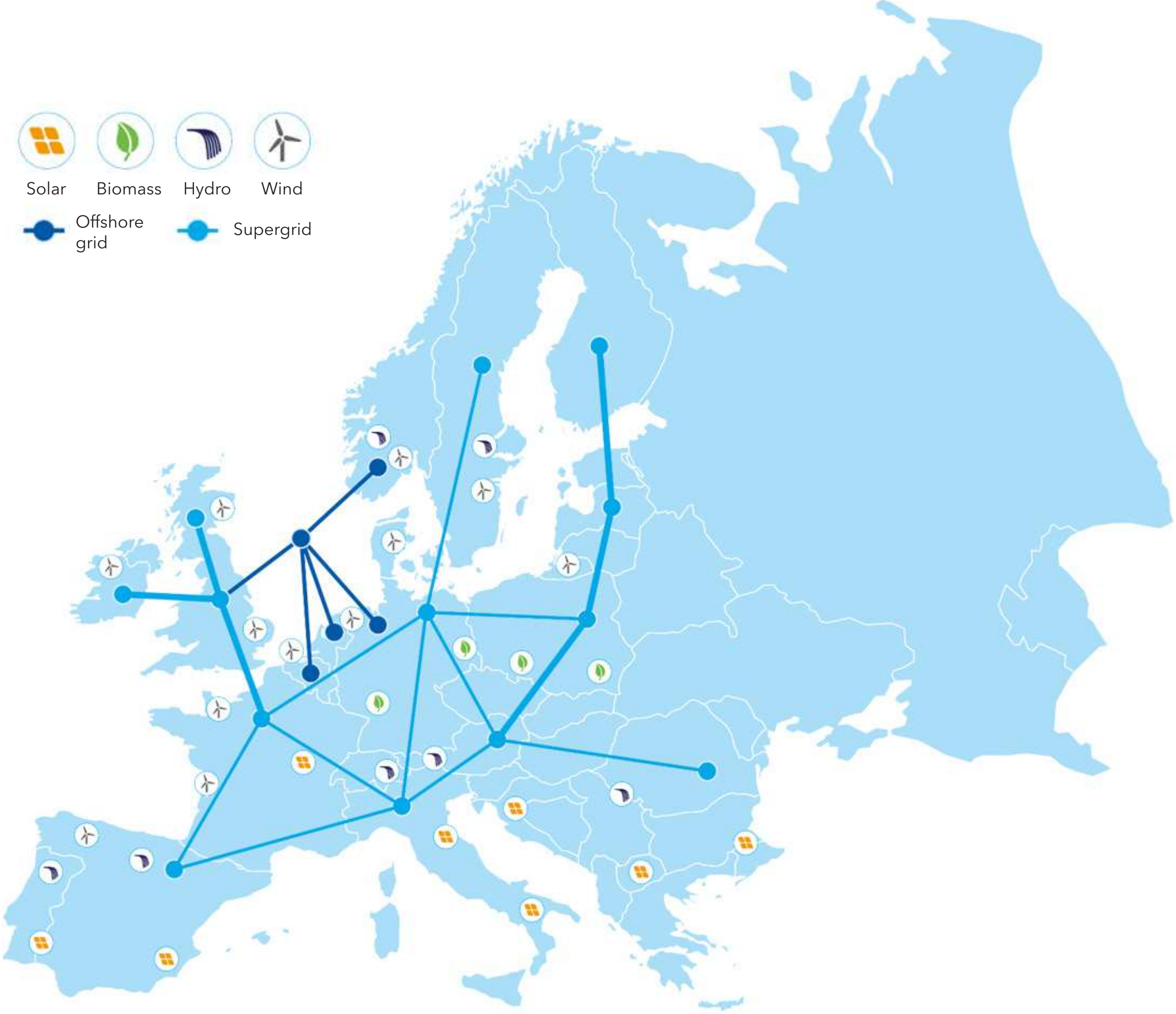


Figure 23 - The European supergrid for interconnection of RES and major load centres

Grid reinforcement at both transmission and distribution level increases the number of connections and/or transport capacity between connected areas and nodes.
This allows to:

- connect remote areas with large RES potential to existing networks, thereby increasing the share of RES in the generation mix on the way to achieving climate change targets
- enlarge the connected geographical area within which supply and demand, and different types of RES (wind, solar, hydroelectric, waves, biomass), can be balanced
- deal with large inflows of variable RES and prevent curtailment by alleviating congestions
- increase grid flexibility through situational awareness and control: this allows for real-time dynamic assessments of transport capability, and fast response to contingencies

On the down side, interconnectors and grid reinforcements have high investment costs. Additionally, developing new (inter)connections is time consuming because of the processes of acquiring property, construction, negotiation between different regional agents and acquiring permissions.

To have the full benefit from extended supra-national grid connectivity, the operational platforms and electricity markets of the different interconnected zones and countries need to be coupled and governed under the same regulatory framework.

Renewable energy curtailment

The last source of flexibility involves curtailing RES. The combination of inflexible base generation, variable renewable generation and other, more flexible, conventional generators needs to match demand and network losses. In a situation with a low demand, the total of base generation (at its minimum set point) and variable (uncontrollable) RES might exceed demand, even when all flexible generation is turned off. In this situation, in case exporting power is also impossible, the only option left is to reduce the RES power, i.e. RES curtailment (or RES output peak shaving). RES curtailment may also be necessary if the RES power capacity is larger than the capacity of the grid connection.

Curtailment of variable RES units means switching off or reducing the power output of these units, even when the energy resource (wind or sun) is available at that time. This means that the curtailed energy is lost and cannot be retrieved at a later moment, thereby decreasing the share of electricity produced by RES. Therefore, RES curtailment is undesirable from a societal point of view. Furthermore, it increases the average cost of the RES electricity produced.

Preventing curtailment is not straightforward, however. It could be mitigated through energy storage, but that is generally an expensive option. Curtailing RES, although not desirable from a societal point of view, might be the most economic option for system balancing in many situations.

In most cases, RES curtailment can be a temporary measure, to allow new RES units to be constructed and operated in advance of transmission or distribution reinforcement, which is slower.
For example, the UK has the 'Connect and Manage' system in place for this purpose [18].

On the other hand, curtailment of the RES peak can be a very logic action. In solar PV systems it is already common practice to under-dimension the PV inverter, which is a form of curtailment. This makes economic sense, because the power peak is reduced by 10% or more, but the yearly energy output is reduced just very slightly. If compensation measures (incentives) could be developed for RES generators, this peak curtailment could become a more permanent measure.

BARRIERS FOR DEPLOYMENT OF FLEXIBILITY

Although there is a variety of resources that can deliver flexibility, there are still barriers that prevent their widespread implementation and cost-effective operation. Apart from the technical barriers addressed above, including risks associated with ICT systems and cyber security, these are barriers regarding regulations, market participation and economics.

REGULATORY BARRIERS

For certain flexibility resources, such as energy storage systems and demand response schemes, regulatory barriers exist regarding the parties that can own and operate them. Additionally, the classification of a power system load as being either demand or generation, limits the optimal exploitation of flexibility resources like storage systems, as they can both absorb and deliver power, possibly leading to unclear market registration requirements and unfair grid connection costs. The regulatory barriers introduce an uncertain investment climate and under-utilised market participation potential for flexibility resources. Furthermore, the power system that needs different flexibility services, may get stuck with resources obeying the present restrictive regulations, that are economically less favourable than new solutions not fitting into the regulations.

Ownership of energy storage is an important barrier. On the one hand, storage can be defined as a supply or demand asset, following market competition rules. On the other hand, storage could fulfil network functions as a grid asset, e.g. congestion relief, but then it is not allowed to interfere with the market rules. Therefore, depending on the party owning the unit, its operational potential could be limited because of the conventional regulations. Moreover, for flexibility resources to be used and fully exploited in internationally interconnected power systems, regulatory frameworks must be harmonised across countries. One improvement in Europe is the EU Winter Package, “Clean Energy for All Europeans” [19], that proposes new developments in the area of market design, market players and technologies such as energy storage, to facilitate flexibility in the system.

Capacity payments and markets will significantly affect the income potential of generation assets and other resources of flexibility. This is especially true for storage facilities, since they can offer both generation and absorption capacity at the same time. Depending on the specific national regulations, capacity markets and mechanisms can have a positive or negative impact on the remunerations of storage facilities.

MARKET/ECONOMIC BARRIERS

Apart from the high investment costs, for example of energy storage, the available market mechanisms and pricing of flexibility services are currently not leading to adequately appreciating the value of flexibility. Very little markets, for instance, have locational or zonal energy prices, implying that storage cannot fully capture the system benefits of congestion alleviations. This uncertainty in revenue for flexibility and the uncertainty in the combination (stacking) of services and markets to earn revenue, is a main barrier for the investment in flexibility resources.

Adequate valuation of flexibility would ideally require a dual-sided market, as is the case in the energy-only markets, with not just one party purchasing flexibility offered by a range of agents, but more buying parties. A large barrier in this is the participation of small consumers in providing flexibility services to the electricity supply system, due to their limited power capacity and lack of organisation. To improve this, aggregator schemes could help by combining small flexibility services into one traded service. Examples of these are Community energy schemes in the UK [20], the USEF framework and research projects like VIMSEN.

Additionally, since flexibility counteracts variability in the system, predicting potential revenues is another challenge, but of major importance to encourage investment. Economic efficiency of energy storage, when only operating for a single flexibility service, has been demonstrated as challenging. Flexibility resources require operational strategies able to maximise their revenues by providing different flexibility services, both market-based and regulated, and stacking the combined revenues. Focussing on one service, e.g. wholesale market trading, is likely to capture only a part of the total system value. Quantifying revenues and defining operational strategies over various markets, presents a complex problem. These multi-objective operational strategies are, however, required to anticipate on uncertainty and capture the full value of a flexibility resource in demonstrating a positive business case.

DNV GL has developed the StRe@m model, which is able to assess and analyse the short and long term business case of flexibility resources whilst taking into account stackable revenues. The following chapter summarises the approach of the developed model and provides an overview of study cases of the business case of battery storage, a gas engine and a pumped hydro storage plant.

eSTORAGE

eStorage is a project consortium supported by the European Commission, working to improve the use of renewable energies through energy storage. The consortium consists of a multidisciplinary team, gathering big European players from the entire electricity value chain.

The partners' expertise includes:

- Expertise in electricity generation and transmission
- Research activities and impact studies
- State-of-the-art hydro power and grid technologies
- Project management

The project team - EDF, Elia, Imperial College, GE, DNV GL and Algoé - is supported by an advisory board including the European Association for Storage of Energy (EASE). The consortium has been awarded a grant by the European Commission (Directorate-General for Research, in the frame of the "FP7 Cooperation: Energy" program) under number 295367.
More information can be found on the project website: http://www.estorage-project.eu/

BUSINESS CASE ANALYSIS

A cost-benefit analysis is of key importance when assessing flexibility options. This is especially true for storage systems, because they generally compete with other flexibility solutions. Moreover, multiple services should be considered for storage, to optimise its business case (or even make it positive). Quantifying revenues and defining operational strategies over various markets and services presents a complex problem, not in the least because of the uncertainty in future market and pricing developments. For analysis of these business cases, versatile tools are needed. One such tools is the StRe@M model developed by DNV GL. This tool can assess the short and long-term business case of flexibility resources while considering stackable revenues. StRe@M is presented in this chapter where several study cases for the business case analysis are described.

STUDY CASES

Five different study cases of providing flexibility are explored in this chapter:

1. Two cases (10 MW/20 MWh and 25 MW/50 MWh) of a Li-ion battery active on the spot and balancing market
2. Two cases (10 MW/20 MWh and 25 MW/50 MWh) of a Li-ion battery in combination with demand (14 MW max) and solar-PV generation (50 MWp to optimise for self-consumption
3. Two cases (10 MW/20 MWh and 25 MW/50 MWh) of a Li-ion battery for optimisation of PV self-consumption, while, in addition, allowing a third-party to use the battery on the balancing market
4. A 50 MW gas engine active on the spot and balancing market
5. Conversion of a 255 MW fixed-speed pumped hydro storage plant (PHS) into a variable-speed pumped hydro plant (VS-PHS). A fixed-speed PHS cannot regulate in pumping mode (i.e. it pumps at a fixed power level), while a VS-PHS can regulate in pumping mode and therefore make more revenue on the spot and balancing markets.

For these analyses, the modular approach of StRe@M was used (figure 24). The analyses of the first four cases were performed using historical day-ahead spot price and balancing price curves. The case of the PHS conversion is performed using a scenario for the electricity and balancing market for the year 2030.

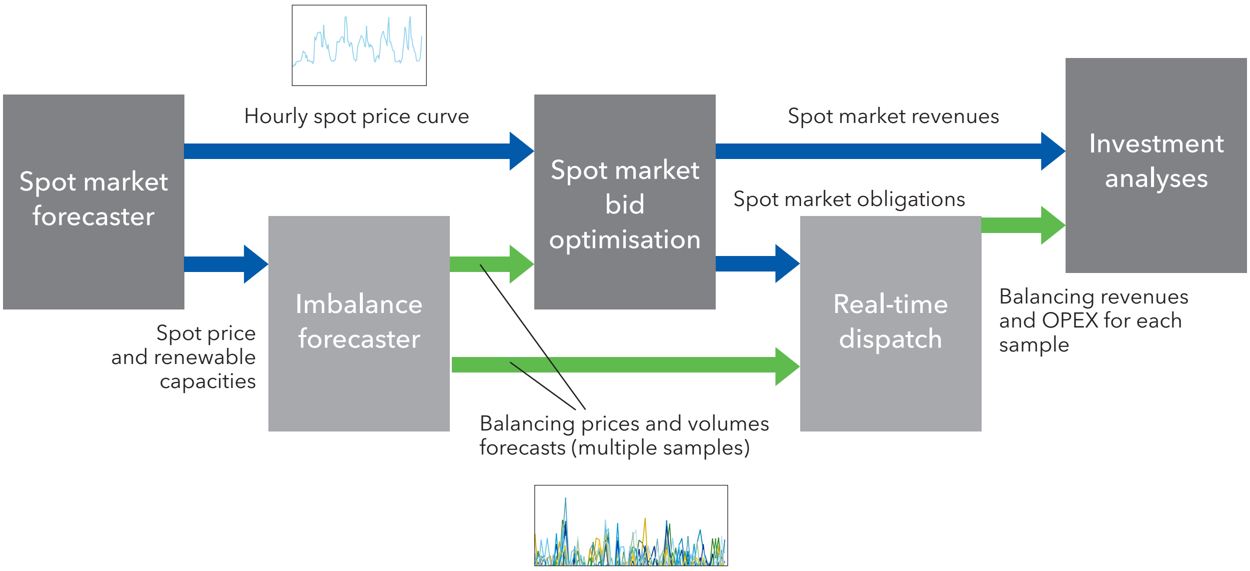


Figure 24 - Overview of the modules and steps performed in the StRe@M approach. Blue arrows: transfer of single time series. Green arrows: transfer of multiple time-series to replicate the forecast uncertainty.

'STRE@M' MARKET MODEL

StRe@M (Storage Revenues at Markets) is an in-house DNV GL tool that determines the business case of energy storage or other resources of flexibility.

StRe@M is a stochastic tool that optimises and estimates the overall revenues of energy storage that can be obtained from the spot, intra-day and balancing markets, taking into account the forecasting uncertainty (of the markets and the RES production) and the technical limitations of the storage or flexibility source.
Based on multiple forecasts of the spot, intra-day and balancing price curves (generated within StRe@M or other tools like PLEXOS), the optimum dispatch and arbitrage between the market places are determined.

The tool can be used for present-day and future scenario calculations; for operation and investment decisions; for different storage technologies; for different spot, intraday and balancing market designs; and for flexible generation and flexible demand sources in general.

STRE@M APPROACH

The optimisation of the portfolio on the spot and balancing market and its real-time dispatch are performed using the StRe@M model. The steps (i.e. “modules”) in this approach are shown in figure 24. Each block represents a module; arrows between the blocks indicate the data-transfer between the modules.

There are five modules in the StRe@M approach:

1. **Spot market forecaster**
   In the study cases presented, the time-series of the Dutch day-ahead spot price of 2015 is used.
2. **Imbalance forecaster**
   The spot price time series is used in the ‘Imbalance forecaster’ module: this module generates multiple synthetic time series of the imbalance volume and the balancing price (based on distributions of 2015 imbalance volumes and balancing prices). These synthetic time series represent the uncertainty (and opportunities) on the balancing market at the time of spot market trade optimisation.
3. **Spot market bid optimisation**
   This module optimises the spot market trades of the flexibility asset (e.g. battery), given the forecast of the spot market prices and the forecasts of the balancing market. The output of the optimisation is a single time series for selling and purchasing electricity from the day-ahead spot market. The optimisation is performed in steps of one day with a time-resolution of 15-minutes.

	BALANCING MARKET		SPOT MARKET	
	10 MW/20 MWh	25 MW/50 MWh	10 MW/20 MWh	25 MW/50 MWh
Volume, charge (GWh)	17	36	4.2	10
Volume, discharge (GWh)	20	41	0.1	0.9
Total volume (GWh)	37	77	4.3	11
Revenues, charge (k€)	1035	2819	-128	-331
Revenues, discharge (k€)	2789	6324	3.0	37
Total annual net revenues (k€)	3824	9142	-125	-293

Table 3 - Breakdown of the traded volumes and revenues for two sizes of the Li-ion battery across charge and discharge actions and across the spot and balancing market (results shown are for one of the 50 statistical variations of the balancing market)

4. **Real-time dispatch**
   This module optimises the real-time dispatch of the battery per Programme Time Unit (PTU), given the forecast of the balancing prices and volumes for the next hour (i.e. only short-term foresight). The obligations with respect to the spot market are known in advance and are implemented as a constraint that must be met. The real-time dispatch is performed multiple times, i.e. separately for each balancing time series from the Imbalance forecaster module.
5. **Investment analyses**
   The investment module performs a Monte Carlo analysis based on the uncertainty in the investment costs and the uncertainty in the combined revenues from the spot and balancing market. As the revenues are determined for one specific year, the investment costs are annuitised and an annuitised net-present-value probability distribution is calculated.

STRE@M RESULTS

Li-ion battery active on spot and balancing market
In the first study case – spot and imbalance trading with a battery – the expected value of the net revenue (based on 50 different statistical variations of the balancing market of one year) is 3.54 M€ for the 10 MW/20 MWh battery and 7.09 M€ for the 25 MW/50 MWh battery for a year that is comparable to the actual year 2015. According to the simulation results, the battery is predominantly active on the balancing market, both in terms of energy volume traded and in terms of revenues (table 3). This means discharging at times of high upward balancing prices and charging at times of low or even negative balancing prices.
This behaviour is illustrated in figure 25.

The net revenue of the 10 MW/20 MWh battery has an expected value of 3.54 M€ per year with a spread from 3.46 to 3.67 M€ (from the Monte Carlo analysis), and for the 25 MW/50 MWh battery this is 7.09 M€ per year with a spread from 5.46 to 8.96 M€.
This corresponds to a payback period of around 3 years for an investment cost of 9.5 M€ for the 10MW/20MWh battery, and for an investment cost of 23.8 M€ for the 25MW/50MWh battery.
The expected value of the annuitised Net Present Value is 2.38 M€/yr for the 10MW/20 MWh battery with a probability distribution from 2.16 to 2.62 M€/yr, and 4.18 M€/yr for the 25 MW/50 MWh battery with a probability distribution from 2.22 to 6.33 M€/yr.

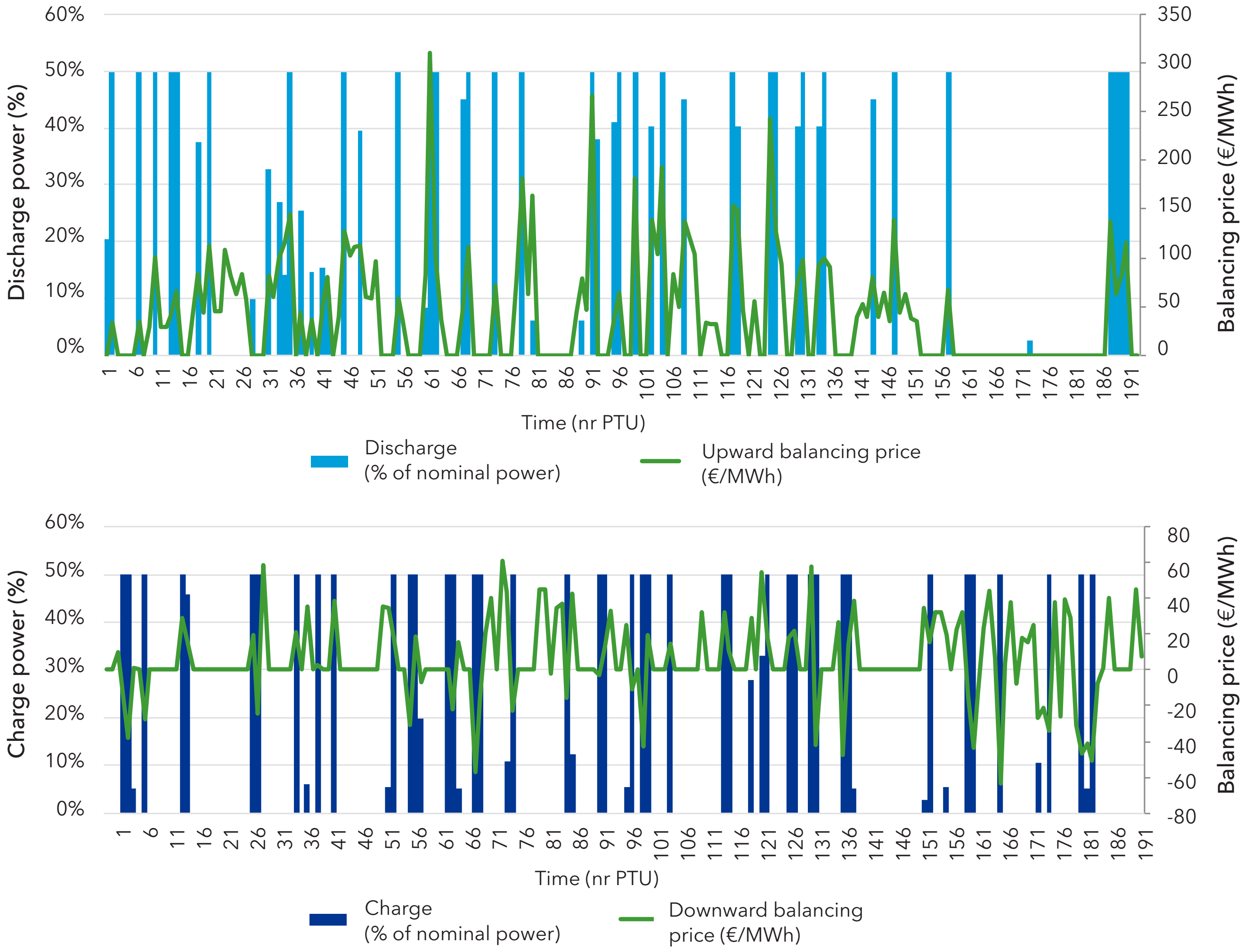


Figure 25 - Illustrative time-series of the discharge (top) and charge (bottom) actions of the battery versus the balancing prices (192 PTUs = 2 days shown)

The results of the StRe@M model show that the main revenue potential for storage in The Netherlands is in the balancing market (that is, FRR), when compared to the spot market. This general conclusion is also valid in other European countries with a spot market and market-based balancing services.

The current approach of StRe@M leads to an overestimation of the revenues from the balancing market, as it assumes a perfect foresight for the balancing prices in the next hour (consisting of 4 PTUs). This overestimation can be put in perspective when comparing this result with the present FRR and FCR markets.

Almost all large-scale storage systems, mainly in Germany, The Netherlands and the United Kingdom, participate in the FCR market rather than the FRR market. This suggest that the expected revenues from FCR in real life are higher than those from FRR. The current remuneration for FCR in The Netherlands is 2.7 k€/MW/week on average. The simulated yearly net revenue for FRR, equal to 1.92 M€, corresponds to 3.7 k€/MW/week, which is higher than FCR. This is unexpected because of the present market participations mentioned above. On the other hand, this indicates that FCR and FRR revenues may be close, and that, with sufficient foresight, a switch could be made from FCR to FRR in case the average FCR remuneration decreases in the future.

Battery for self-consumption optimisation
In the second study case – self-consumption – a large office complex (14 MW peak load) with solar-PV (50 MWp) and a battery is explored. The study case is carried out twice, once for a battery of 10 MW/20 MWh and once for a battery of 25 MW/50 MWh. The consumption profile and the PV generation profile are illustrated in figure 26.

The office owner has an agreement with his electricity supplier: he can consume electricity at 0.06 €/kWh and feed in at 0.03 €/kWh. In addition, an alternative case with a feed-in tariff of 0.00 €/kWh is analysed.

Five cases are compared:

1. the electricity costs of the office without PV and without battery
2. the electricity costs of the office plus PV (without battery), with:
   a. 0.03 €/kWh feed-in tariff, or
   b. 0.00 €/kWh feed-in tariff
3. the electricity costs of the office with PV and with battery, with:
   a. 0.03 €/kWh feed-in tariff, or
   b. 0.00 €/kWh feed-in tariff

For each case, there is no forecasting required as the consumption price and feed-in tariff are constant in time. For example, in case 3, the battery starts charging whenever the PV generation exceeds the consumption and discharges whenever the consumption exceeds the generation. (In case of variation of the tariffs in time, a more sophisticated controller would be required.)

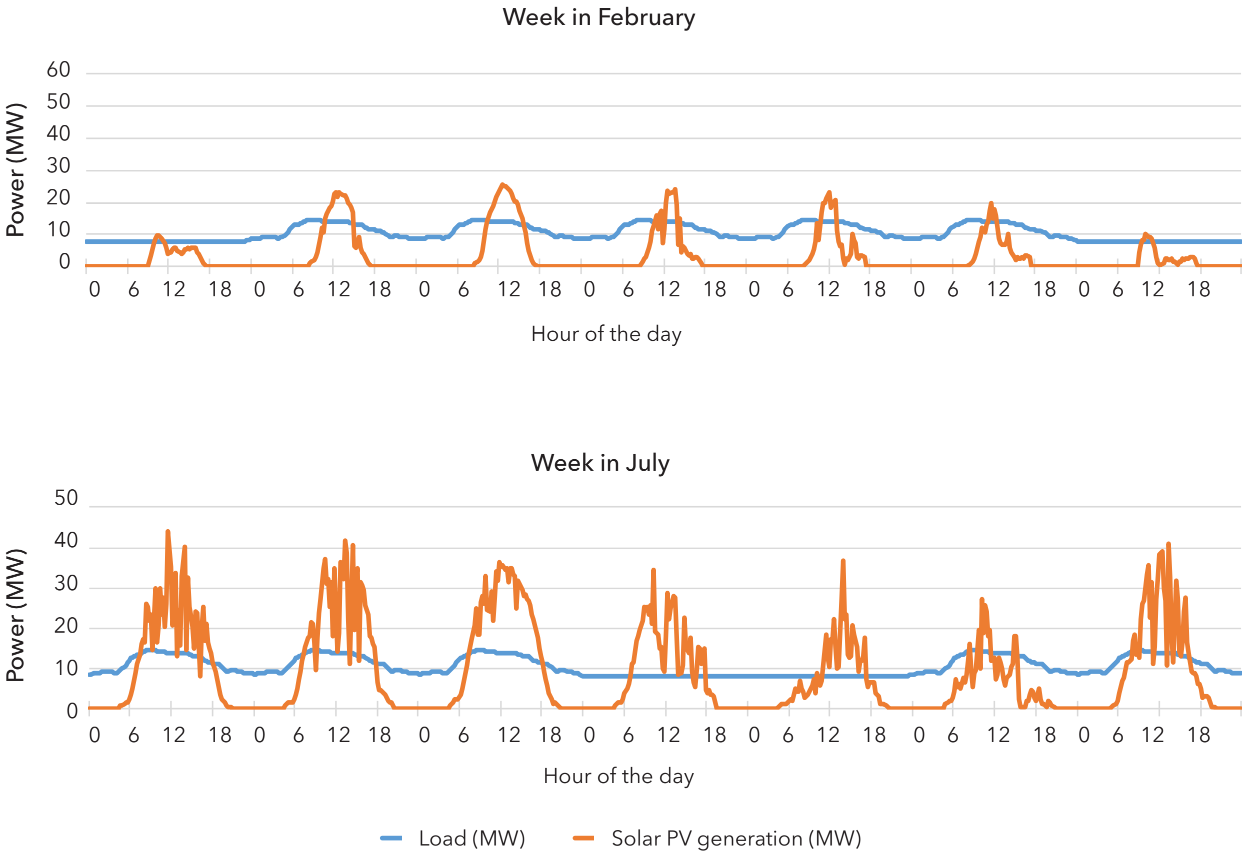


Figure 26 - Illustrative time series showing the demand profile and the PV generation profile of 7 days in winter (top) and in summer (bottom)

CASE	PV	BATTERY	FEED-IN TARIFF €/KWH	SELF-CONSUMPTION RATE (% OF PV POWER TO LOAD)		NET ELECTRICITY CONSUMPTION COSTS (M€/YEAR)	
1.	No	No	–	–		5.5	
2a.	Yes	No	0.03	66%		3.1	
2b.	Yes	No	0	66%		3.6	
				10 MW/20 MWH	25 MW/50 MWH	10 MW/20 MWH	25 MW/50 MWH
3a.	Yes	Yes	0.03	76%	84%	3.1	3.0
3b.	Yes	Yes	0			3.4	3.2

Table 4 - Electricity consumption costs for five cases in self-consumption optimisation

The resulting electricity consumption costs of the five cases are shown in table 4.
Table 4 shows that adding PV panels leads to a reduction in the annual electricity costs. The peak in demand and generation largely coincides (figure 26), allowing a significant amount of self-consumption from the PV panels, even without storage. The PV panels reduce the consumption from the grid by around 31 GWh and create a feed-in of around 16 GWh into the grid. Depending on the feed-in tariff, the cost reduction is 2.0 to 2.4 M€/year.
Adding a battery to the system has an additional benefit: the self-consumption of the PV electricity increases from 31 GWh to 36 GWh and 40 GWh for the 10 MW/20 MWh and the 25 MW/50 MWh batteries, respectively. The associated additional decrease in electricity costs is 0.5 or 0.6 M€/year (in case of 0.03 €/kWh feed-in tariff) to 0.2 or 0.4 M€/year (without feed-in compensation).

Discussion
The reduction in costs of 200 to 600 thousand euro per annum is small compared to the investment costs of 9.5 M€ and 23.8 M€ for the 10 MW/20 MWh and 25 MW/50 MWh battery, respectively. This would result in a payback time of 20 to 60 years, depending on battery size and level of feed-in tariff. The main reason for the limited benefit of the battery is the limited number of cycles (less than one per day on average) in this application.

In case of a larger price spread between the electricity bought and feed-in, the business case for storage for self-consumption could be more attractive. The following section investigates the potential benefits of stacking of revenues from self-consumption and balancing services.

Battery for self-consumption optimisation and balancing market
In this case, first self-consumption is applied and then the balancing market is serviced (through a third party). The battery owner submits his 'battery charge and discharge plan' for maximum self-consumption to the third party. The third party can use the remainder of the battery power and energy for balancing services. Hence, a day-ahead forecast of the use of the battery for self-consumption is made. This forecast takes the uncertainty in the PV generation into account.

Figure 27 provides an illustration of how the battery is used: the priority is to maximise the self-consumption of the solar-PV electricity.
This effect is shown by the charging of the battery at times when the PV generation exceeds the local consumption and the discharging of the battery at times with low or no PV generation.

The remaining battery power and energy content is used for the balancing market, providing upward and downward balancing energy.

This analysis shows that the combination of maximising self-consumption and providing balancing energy leads to an overall revenue that is comparable to the sum of the separate revenues, see table 5.

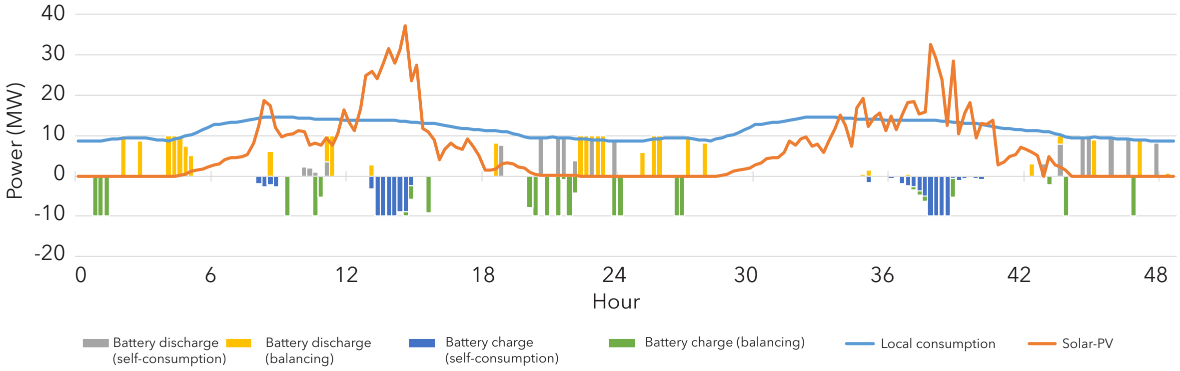


Figure 27 - Example period illustrating the utilisation of the battery for the combination of self-consumption optimisation and providing energy for the balancing market

	BALANCING MARKET REVENUES (M€/YEAR)		ELECTRICITY CONSUMPTION SAVINGS (M€/YEAR)	
	10 MW/20 MWH	25 MW/50 MWH	10 MW/20 MWH	25 MW/50 MWH
Self-consumption optimisation or balancing service only	3.8	9.1	2.1	2.3
Stacked services	3.7	6.7	2.4	2.5

Table 5 - Revenues and cost savings using a battery (with PV) for self-consumption optimisation and balancing market participation

Gas engine
A gas engine is a fast-start conventional generator with high running cost. Consequently, the dispatch of the gas engine purely on the spot market (in the Netherlands) turns out to be limited to a few hours during two days in November with high peak prices (figure 28; assuming there are no other reasons for running the engine, e.g. no heat delivery obligations). The main reason for the few operating hours is the fact that the Dutch spot market is dominated by coal-fired and CCGT generation, wherein gas engines are too expensive.

Since the gas engine is a fast-start generator, an alternative option is providing short-term flexibility, e.g. when balancing prices are extremely high (~200 €/MWh) and expected to remain at that level for several PTUs. An analysis of the balancing market revenue potential for a gas engine has been performed using the StRe@M approach, which is discussed below. Another option for gas engines is to provide standing reserve capacity in case of scarcity of (conventional) generation resources.

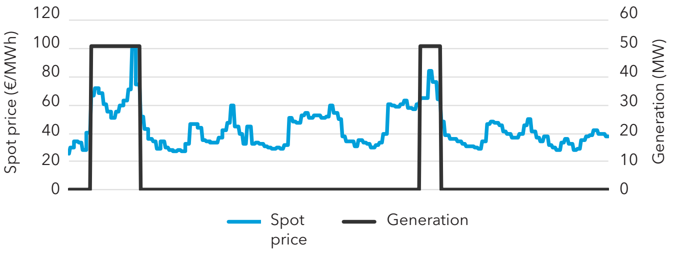


Figure 28 - The period in November where the gas engine is active on the spot market for two days (black line)

With StRe@m, the gas engine's annual revenues from the balancing market were estimated. A 50 MW gas engine with an efficiency of 39% is modelled. For this analysis, only the real-time dispatch module is used: the gas engine is assumed to be only active on the balancing market and not on the day-ahead spot market. Consequently, it is relevant that the operator has an accurate short-term forecast of the balancing prices: a perfect foresight of 30 minutes is assumed.

Based on the analyses, the gas engine can earn 7 M€/yr on average. The analyses assume a relatively dynamic start-stop behaviour with 6 starts per day on average. Implementing a larger start cost figure to incorporate risk premium (due to uncertainty in the actual balancing price developments) will reduce the number of start-stop cycles, but will also result in a reduction in revenues. Assuming investment costs of 900 €/kW, a 6.5 year payback period is obtained in this case.

Pumped hydro storage plant conversion

A conventional pumped hydro-electric storage (PHS) plant can only pump water up at one fixed speed, that is one fixed power level. Hence it can only regulate its power output in generation (i.e. discharging) mode (between its minimum stable level and its maximum generation capacity); in power consumption (i.e. charging) mode, however, it can only withdraw power from the grid at one fixed load. It is possible to convert an existing (fixed-speed) PHS plant into a variable-speed (VS-PHS) plant that can also regulate in pumping mode. This would increase the capability of providing flexible balancing power, allowing an increase in revenue from the market. In this section, the business case of a conversion of a 255 MW fixed-speed PHS into a VS-PHS that is active on the spot and balancing markets is explored.
This is assessed using a scenario for Belgium in 2030 [13].

Figure 29 shows an example of the real-time dispatch of a VS-PHS calculated using the StRe@M approach. The figure shows that in the sixth hour, the VS-PHS provides upward balancing energy as its real-time pump load (light green bar) is below the planned spot market pump load (green area). Furthermore, in hour 7 and 8, there are very low downward balancing prices, such that the pump of the VS-PHS is started purely for the balancing market.

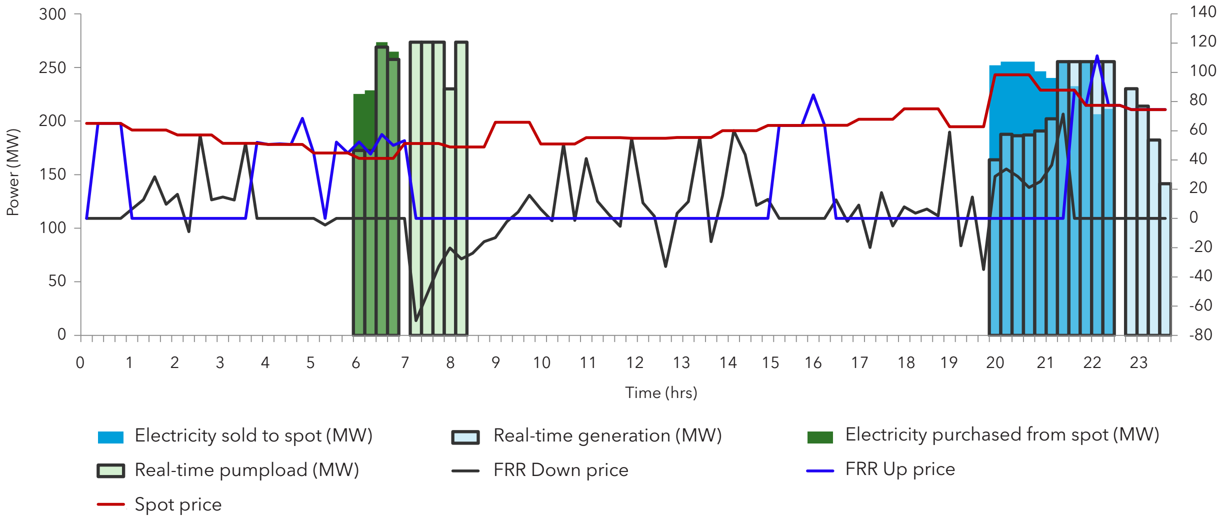


Figure 29 - Example of VS-PHS dispatch on spot market (green and blue areas) and balancing market (light green and light blue bars). The solid lines indicate price signals.

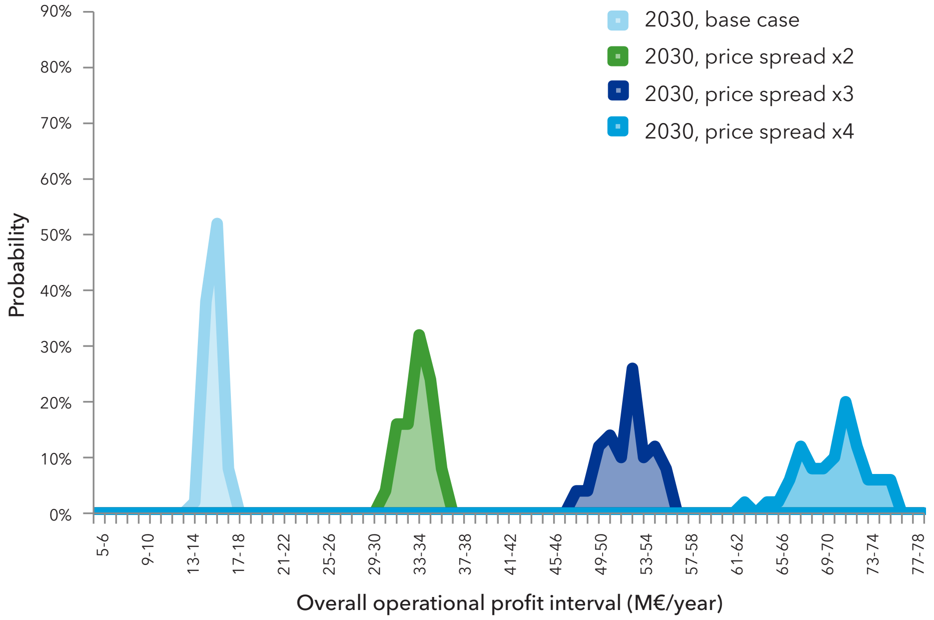


Figure 30 - Probability distributions for the operational profits of a VS-PHS for different balancing price spread regimes

Based on the spot market transactions (from StRe@M's spot market optimisation) and the balancing market revenues (from the Monte Carlo analysis), a distribution of the overall operational net revenues can be obtained. This analysis is performed for four cases that differ in the spread between the spot and balancing market prices. The calculation of the operational net revenue is performed for both VS PHS and (fixed-speed) PHS; the difference in revenues is the benefit of the conversion from fixed to variable speed PHS. Figure 30 shows the probability distributions of the operational profits of a VS PHS for the different balancing price spread regimes. Table 5 shows the difference between the VS PHS's and the PHS's expected values of the annual operational profits.

Increasing the balancing price spreads shows a proportional increase in revenues for VS PHS (figure 30).

This is due to the arbitrage that is performed: selling electricity on the spot market and buying it back on the balancing market when balancing prices are low. The NPV of the VS PHS has been calculated too for the cases mentioned. The NPV calculations include the additional investment cost of VS PHS compared to fixed-speed PHS, being 49 M€. The results are shown in table 6. These results show that there is a positive business case for the conversion to VS PHS for all four cases analysed.

The difference in operational profits between PHS and VS PHS is due to the increased flexibility of providing downward and upward balancing energy while pumping at low spot market prices, and due to an increase in the round-trip efficiency from 80% to 85%. The increase in round-trip efficiency results in increased revenues in both the spot and balancing markets.

ALL NUMBERS IN M€/YEAR	BASE CASE 2030	PRICE SPREAD x2	PRICE SPREAD x3	PRICE SPREAD x4
Increased annual operational profits	5	10	15	23
Annuitised NPV	1	6	11	19

Table 6 - Increase in expected revenues of a VS-PHS compared to a fixed-speed PHS

CONCLUSION

This paper explains the need for flexibility in the current and future power system, and presents the types of services for flexibility, the available sources of flexibility, the existing barriers for deploying flexibility, and a method to calculate the business case for a combination of flexibility applications.

In the electric power system, electricity supply needs to be balanced with electricity demand and network losses at all times to maintain safe, dependable and stable system operation. Flexibility within the power system is hence required to compensate for variability in the system and maintain its balance.

Historically, variability and uncertainty in the system mainly occurred on the demand side. This variability was to be matched top down through flexible conventional power plants through a reliable grid. The ongoing changes in energy production and consumption – creating more variability and uncertainty – ask for other means of flexibility in addition to the conventional ones. The main changes are the increase of renewable energy sources, both on large-scale and distributed level, and the increase in power consumption and demand variability by the transportation and heating & cooling sectors. The latter also provide a means of flexibility, that is demand side management. This means that new power consumers, like electric vehicle chargers and electrical heat pumps, can respond to flexibility requests from the power system by adapting their consumption pattern. This new ecosystem creates the smart grid, where renewable energy sources, flexible consumers and energy storage systems cooperate in a collaborative environment.

The different sources of flexibility may have technological and cost-related barriers to prevent their uptake. There are also barriers in regulation, standardisation and energy market rules. However, regulations, standards and markets are being developed worldwide to facilitate emerging flexibility solutions, like energy storage and demand response. One of the standardisation initiatives is DNV GL's recommended practice on safety, operation and performance of grid-connected energy storage systems, GRIDSTOR.

For most flexibility resources, especially energy storage, a single flexibility service will not ensure a positive business case. Stackable revenues, by combining operational services in different markets and time scales, will therefore become important to render the business case worthwhile. The StRe@M model, developed by DNV GL, can capture and determine the stackable revenues of different services provided by a single flexibility resource, such as a Li-ion battery, demand response or pumped hydro-electric storage. The StRe@M model optimises the portfolio of flexibility services, while considering uncertainty in the forecasts of the market prices and RES generation for the next hour(s), day(s), and longer periods. Therefore, StRe@M is also ideally suited for the analysis of the value of flexibility in future scenarios.

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