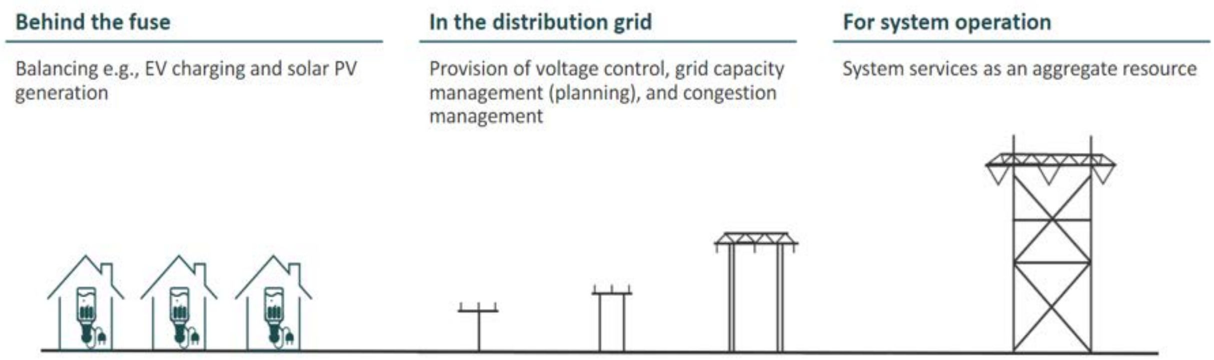
EKSTERN RAPPORT

Nr. 5/2021

# Value of flexibility from electrical storage water heaters

*Thema Consulting Group and Danish Technological Institute*



# NVE Ekstern rapport nr. 5/2021

## Value of flexibility from electrical storage water heaters

**Published by:** Norges vassdrags- og energidirektorat

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**Cover photo:** Thema Consulting Group

**ISBN:** 978-82-410-2108-4

**ISSN:** 2535-8235

**Abstract:** Flexibility in many forms and locations will be necessary for cost-efficient and safe operation and balancing of the future power system. This report explores the potential role and value of flexibility provided by electrical storage water heaters (ESWH). ESWH can provide a range of relevant flexibility services, ranging from fast response to diurnal load shifting, and both locally and on a system level. It can be used within a building (behind the fuse), within a smaller grid area or local energy community, within a distribution grid, and in the central energy system, both in terms of energy balancing and grid operation. The value of the flexibility depends on the needed flexibility characteristics and the cost of alternatives. The value estimates for individual flexibility services range from 8 to almost 500 €/kW/year, depending on the market and the time horizon. However, while new flexibility technologies and solutions are developed, ESWHs represent an existing and proven flexibility resource that is highly distributed and already utilized in several systems.

**Key words:** ecodesign, energy label, 812/2013, 814/2013, electrical storage water heaters, ESWH, consumers, peak shaving, load shifting, demand side, flexibility, cost, power system, electricity system, smart grid, smart appliance, smart control, thermal battery, electrical battery, demand response, load shifting, grid balancing, local voltage control, frequency control, DSO, TSO, zero carbon, charging, tapping profile, ripple control, Norway, France, Finland, Sweden, Germany, Switzerland.

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March, 2021

# Preface

The European Union is making substantial efforts to reduce $CO_2$ emissions in order to meet global climate challenges. Phasing out fossil energy generation and decarbonisation of the European heating sector will contribute to that goal. However, intermittent electricity generation such as wind and solar, increases the importance of demand-side flexibility.

In many countries, electric storage water heaters (ESWHs) represent a large and important source of flexibility. The total stock of ESWHs in Europe corresponds to the daily storage capacity of more than 120 GWh and a daily flexible capacity of 20 GW. This equals a third of the installed nuclear capacity in France, the entire installed capacity of Czechia, or more than the generation capacity in Finland.

The analyses in this report are conducted by Thema Consulting Group, commissioned by NVE. The report explores the size and the potential value of the flexibility in the stock of ESWHs in the European electricity system. It describes the flexibility characteristics of ESWHs and how ESWHs have several advantages compared to other sources of flexibility: fast reacting, high cyclicity, low latency, short resting time, defined capacity, affordable, and low impact on life expectancy and user comfort.

A narrow focus on energy efficiency requirements at single product level may reduce the ability of products to provide important flexibility and power reducing capabilities for the overall energy system and the distribution grid. Large water heaters with load profiles XXL-4XL were phased out from the single market in 2018, as a result of the strict ecodesign energy efficiency requirements in regulation 814/2013. The regulation is currently being revised by the EU.  The energy efficiency requirements introduced in 2018 reduced the flexibility contribution from new ESWHs. Further restrictions on the ESWH will remove or significantly reduce flexibility from ESWH.

The report shows value estimates for alternative flexibility services that range from 8 to almost 500 €/kW/year, depending on the market and the time horizon. It concludes that flexibility from ESWHs can provide local balancing in interaction with local demand and local generation, like Electric Vehicle charging and PhotoVoltaic generation. The ESWHs represent flexibility within a building (behind the fuse), within a smaller grid area or local energy community, within a distribution grid, and in the central energy system, both in terms of energy balancing and grid operation.

We hope this report gives better insight into how ESHWs can contribute to flexibility in an energy system with an increasing share of intermittent electricity production.

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THEMA CONSULTING GROUP

Public

ISBN nr. 978-82-8368-079-9


**Commissioned by NVE**

2/17/2021

THEMA Report 2020-17

| About the project | | About the report | |
|---|---|---|---|
| Project number: | NVE-20-01 | Report name: | Value of flexibility from electrical storage water heaters |
| Project name: | The value of ESWHs as flexible distributed and aggregated storage facility for Demand Side Management | Report number: | 2020-17 |
| Client: | Norwegian Water Resources and Energy Directorate, NVE | ISBN-number: | 978-82-8368-079-9 |
| Project leader: | Berit Tennbakk | Availability: | Public |
| Project participants: | Mina B. Ryssdal<br>Kristine Fiksen<br>Ole-Kristian Ådnanes<br>Christian Holm Christiansen (Teknologisk Institut) | Final version: | February 17, 2021 |


## Brief summary


Flexibility in many forms and locations will be necessary in for cost-efficient and safe operation and balancing of the future power system. This report explores the potential role and value of flexibility provided by Electrical water heaters (ESWH). ESWH can provide a range of relevant flexibility services, ranging from fast response to diurnal load shifting, and both locally and on a system level. The value of the flexibility depends on the needed flexibility characteristics and the cost of alternatives. The value estimates for individual flexibility services range from 8 to almost 500 €/kW/year, depending on the market and the time horizon. However, while new solutions and new technologies are developed, ESWHs represent an existing and proven flexibility resource that is highly distributed and already utilized in several systems.


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THEMA Consulting Group is a Norwegian consulting firm focused on Nordic and European energy issues, and specializing in market analysis, market design and business strategy.

## Disclaimer

## CONTENT

# SUMMARY AND CONCLUSIONS

*The value of flexible resources in the electricity system is set to increase with the transition to a future low-carbon and renewable electricity system. Flexibility in many forms and locations will be needed in the balancing of the market itself, but also in grid management and to defer massive grid investments, and locally, behind the fuse and in local smart grids. Electrical water heaters (ESWH) represent a distributed and highly flexible resource that is already utilized in several systems. The future value of the flexibility of ESWHs depends on the availability and costs of other solutions as well. However, while new solutions and new technologies are developed, ESWHs represent an existing and proven flexibility resource.*

### Demand flexibility is needed to manage the power system of the future

Traditionally, the balancing of the electricity system in Europe has been secured by large, thermal power plant located close to consumption centres. In contrast, the future low-carbon energy system will be dominated by intermittent and distributed generation capacity, and system balancing will have to be secured by new technologies, such as batteries and hydrogen, and by engaging demand-side flexibility to a much larger extent.

Electrical storage water heaters (ESWH) are already used as a flexible resource in several European electricity systems. In this study, we assess the potential value that the flexibility of ESWHs represent. The background for the study is the concern that this flexibility potential may be lost if the application of energy efficiency standards for ESWHs only regard the efficiency of the singular product while not taking into account their potential contribution to system efficiency in tomorrow's decarbonized energy sector.

### Charging of ESWHs can be shifted to help reduce peaks in the power system …

The electricity consumption of ESWHs is highly flexible. Due to the capacity to store hot water, the charging of ESWHs can be shifted without loss of comfort to the consumer, largely without loss of efficiency, and without reducing the lifetime of the ESWH. And they react fast, the load can be automatically switched off and on in a matter of seconds.

If the ESWHs are not controlled, they will typically be charged during the morning and afternoon peaks in the power system. Charging can easily be shifted to off-peak periods via simple or smart signals. By reducing peak load, the need for costly investments in both generation and grid capacity can be reduced.

### … and already represents a significant demand-flexibility potential

ESWHs are widespread in many European countries. In total, the stock of primary water heaters in Europe make up a daily flexible capacity corresponding to a third of the nuclear capacity in France and the entire installed capacity of Czechia. The daily controllable storage capacity corresponds to the total storage capacity of 3 million Nissan LEAF EVs. Moreover, ESWHs represent a highly distributed flexibility potential as they are already found in numerous buildings, including homes.

### ESWHs may reduce peaks and increase self-consumption

The energy transition and changes in consumption patterns are changing electricity demand and peak loads. In households, the introduction of induction hobs, more electrical heating, high pressure washers, some heat pumps without soft start, and electrical vehicle charging implies higher peak loads. Roof-top solar PVs imply a demand for storage when household generation exceeds household consumption. By storing excess PV generation, studies show that self-consumption can increase as much as 60 percent.

Not all European households have fuse and connection capacities that readily accommodate local EV charging and PV generation. While the EV charging profile can also be controlled, interaction



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with ESWHs can provide additional flexibility at a low cost. Hence, costs related to expansion of fuse size and connection capacity can be avoided and the peak load reduced.

### Flexibility is an alternative to expansion of distribution grid capacity

In distribution grids, utilizing flexibility can be the cheapest and fastest way to handle more peaky load patterns and the connection of new consumption and distributed generation. When peak load increases but occurs in fewer hours and less frequently, and demand projections become more uncertain, the business case for grid capacity investments grows weaker. Moreover, grid expansion is costly and takes time, and access to flexibility can make it possible to connect new generation and load without having to wait for capacity expansion (early connection).

### Relevant flexibility can be provided by several sources

The attractiveness of flexible use of ESWHs in grid operation and for system balancing depends on the characteristics of the challenges at hand and the costs of alternative flexibility solutions.

Studies show that flexibility, if used in a grid-friendly manner, can contribute to more efficient grid operation, better planning and reduced investments via different services, such as voltage control, grid capacity management, and congestion management. While several flexibility resources can contribute, ESWHs have the necessary characteristics – well-defined storage, high cyclicity, short resting time – to provide all the relevant distribution grid flexibility services.

Demand-side flexibility can come from ESWHs, EVs, heat pumps and changes in behaviour. Alternatives to demand-side flexibility include system battery solutions and possibly contributions by distributed generation. Different flexibility alternatives have different characteristic and may complement each other.

### The value of flexibility from ESWHs depends on the costs of alternative sources

The system value of ESWH flexibility is the alternative cost, i.e. the costs that are incurred if the flexibility from ESWHs is not available in future. Ideally, market prices would reflect the alternative value of ESWH flexibility. If market prices are not available, an alternative approach is to estimate the costs of the cheapest relevant alternative.

We have made estimates based on both approaches and for different flexibility services. Relevant data is however hard to come by and the estimates should be viewed as illustrative guesstimates rather than best guesses.

#### *Estimates based on market prices*

- DSO flexibility prices: The first group of estimates is based on the total per kW remuneration (availability and activation) for different flexibility services for a GB DSO. DSO flexibility markets are however in their infancy, and current market prices are but weak indicators of the value of flexibility for DSOs.
- Frequency Containment Reserve prices: A Swedish pilot tested the use of aggregated ESWH participation in the FCR-N market. Based on Swedish 2020 FCR-N prices we have estimated the annual capacity remuneration per kW per year. In addition, net energy compensation would be paid for activation, depending on activation frequency and market prices.

#### *Estimates based on alternative costs*

- System battery costs: Batteries are expected to be necessary to provide flexibility to distribution grids in the future. The cost of batteries with characteristics comparable to ESWH thus indicate the value of future ESWH flexibility. The estimates are based on the per kW capital cost of batteries providing different flexibility services.
- Future redispatch costs: Based on a study by Frontier Economics, the net cost of demand response is compared to the cost of CHP and biomass for future redispatch (upregulation) in Germany.



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- Cost of peak load capacity: The value of flexibility is estimated based on the cost of peak load reserves. In France, the value of ESWHs is generally regarded as most valuable for the balancing supply and demand through down-regulation in peak load hours, thus reducing investments in peak plant capacity.

The estimates are summarized in the table below.

***Summary of alternative value estimates for flexibility provision***

| | Power €/kW/year |
|---|---|
| ***Flexibility market prices*** | |
| *Western Secure market (GB)* | 110 |
| *Western Dynamic market (GB)* | 9.2 |
| *Western Restore market (GB)* | 7.8 |
| *FCR-N market (SE)* | 75 |
| ***Cost of alternatives*** | |
| *Battery cost system stability* | 346–474 |
| *Battery cost wholesale market* | 63–391 |
| *Battery cost behind-the-meter* | 246–336 |
| *CHP and biomass capacity (DE)* | 50 |
| *Peak load reserve* | 40–60 |

Notably, the prices in the DSO markets are far below the cost of batteries. The values are however likely to vary by location, by DSO, and by season. The prices also reflect current values, while battery costs are likely to be a better estimate of the future value of flexibility. Battery costs are however set to be reduced, and the value of flexibility expected to increase in the future.

ESWHs are already aggregated and used by transmission system operators for provision of frequency control and to balance supply and demand in peak hours. All flexibility markets are however not open to participation by aggregated demand-side flexibility yet. In addition, potential flexibility values have been demonstrated in several pilots.

### *Remarks*

It should be noted that the estimates are not readily comparable as they rest on different sources, different services and different assumptions. They do however illustrate that there is a potential significant flexibility value contained in the presence of ESWHs in the electricity systems.

It should also be noted that the estimates are made for singular use cases, while in reality, the flexibility can be used for several purposes and both on distribution and transmission and system level. Still, the values cannot be just be summarized, as there will be some simultaneity in the challenges for which flexibility can be used, and all capacity will not be available at the same time. The extent of such simultaneity will vary with system characteristics.

The future value of flexibility from ESWHs will also depend on the development of marketplaces, alternative technologies, smart technology, and alternative costs, such as the cost of batteries.

### Conclusion: The flexibility characteristics of ESWHs represent a positive option value

In summary, the flexibility from ESWHs can provide local balancing in interaction with local demand and local generation, within a building (behind the fuse), within a smaller grid area or local energy community, within a distribution grid, and in the central energy system, both in terms of energy balancing and grid operation. There are several alternatives to the flexibility offered by ESWHs, but ESWHs have some very attractive characteristics:

- They are highly distributed, which means they can contribute to grid operation in areas with few alternatives

- They can respond fast and frequently to automatic signals with very low cost
- Their flexible use does not depend on substantial additional investment costs nor impose additional costs on the consumer
- The technology to control them is already demonstrated for a long time and in different contexts

In order to utilize the substantial flexibility potential from ESWHs (and other distributed resources), individual loads must be aggregated, aggregators must be given access to flexibility markets, and flexibility markets must be established.

While the value estimates are highly uncertain, it is clear that the volume of flexibility that will be needed and the alternative value of flexibility is set to increase in the future electricity system. It is likely that contributions from several resources will be needed in order to keep costs down.



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# 1 INTRODUCTION

Engaging consumers and utilizing demand-side flexibility in the safe operation of the electricity system is a crucial part of the transition to the European low-carbon economy. While the transition implies replacement of conventional thermal generation with variable renewable generation and electrification that change load patterns, exploiting demand-side flexibility can contribute to lowering total system costs related to investments in generation and grid capacity.

Demand-side flexibility can come from several sources and new smart technology makes it possible to control different parts of end-users' electricity consumption at low cost. Electrical Storage Water Heaters (ESWH), found in many European homes, are highly flexible appliances that in some countries already provide flexibility services to system operators. ESWH may support the power system through energy storage applications enabling very fast reaction times. In future, the flexibility potential in ESWHs may increase as fossil fuel-based water heating is phased out and smart metering and control become widespread.

Now there is a worry that strict energy efficiency requirements in the current Ecodesign regulation (EU) No. 814/2013 and that may result from the ongoing revision of both the Energy Label egulation (EU) No. 812/2013 and the Ecodesign regulation, may effectively remove or significantly reduce the volume and flexibility of ESWHs.

This report explores the potential value of the flexibility contained in the stock of ESWHs in the European electricity system by way of their flexibility characteristics and the cost of alternatives. We start by describing the flexibility characteristics of ESWHs and how ESWH charging may interact with crucial household loads such as EV charging and PV generation behind the fuse. Then we go on to explore the potential cost savings by using ESWH in the operation of distribution and in system operation. In conclusion, we discuss the overall value of ESWHs as a flexible resource and reflect upon the wider implications of forgoing this flexibility potential in the transition to the future zero-carbon energy system.



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# 2 FLEXIBILITY CHARACTERISTICS OF ESWH

*The charging of electrical storage water heaters is highly flexible. Charging can be switched on and off within seconds and the charging pattern can be shifted diurnally, largely without loss of efficiency and without loss in comfort for consumers. The larger the storage tank, the higher the power capacity, and the higher temperature in the tank, the more flexible is the ESWH. The short response time implies that ESWH can contribute to frequency and voltage control in grids. Moreover, controlling ESWH charging can flatten the diurnal load profile of a household significantly. While normal user profiles imply that ESWH charging contribute to the morning and the afternoon peaks, charging can easily be shifted via simple or smart signals. The prevalence of ESWHs differ among European countries. We estimate that the total stock of primary water heaters corresponds to a controllable daily storage capacity of more than 120 GWh and a daily flexible capacity of 20 GW, which is more than the installed generation capacity in Finland.*[1]

## 2.1 What is the flexibility potential of individual ESWH?

Electrical Storage Water Heaters consist of a water storage tank and a heater element. Its basic function is to provide hot water supply to a household or a building. The ability to store hot water for several hours with little loss in temperature, implies that, if beneficial for other reasons, the diurnal heating cycle can be altered independently of the tapping cycle. This flexibility in power demand from water heaters has already been used for balancing in the power systems, e.g. in France, Finland and Switzerland, for several decades, using load management often referred to as “Ripple control”

How flexibly an ESWH can be operated within a day depends on the user profile, the power capacity, and the energy storage capacity.

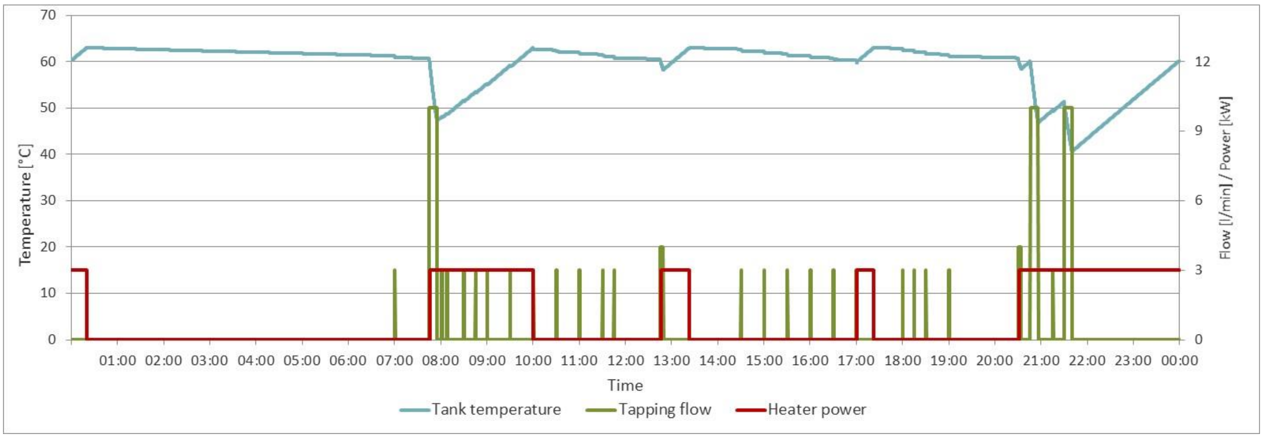
### *User profiles*

In standard usage, the heater element will be turned on and off according to a pre-set water temperature. If the temperature falls below this pre-set level, the heater element will immediately switch on. When the pre-set temperature is reached, the heater element is automatically turned off. Then the tank can store hot water for several hours until hot water is tapped, cold water is inserted, and the water temperature falls.

The tapping profiles of individual ESWH depend on the usage patterns in the residence but with a clear concurrence of consumption between users, which also coincide with the general electricity consumption for the residential sector. Figure 1 shows the user profile of an ESWH according to a standard XL tapping profile used in Ecodesign regulation. The green line bars represent the tapping profile, the blue line the tank temperature, and the red line the power usage of the tank. As seen in the profile below there are some heat losses in the ESWH tank. However, the standing heat loss is relatively small for ESWHs with normal consumption, and in the example below heat loss never causes the temperature to fall below the set-temperature activating the heating power.

[1] Installed power generation capacity in Finland was 17.7 GW in 2019 (Energiavirasto, 2020)

***Figure 1: Example consumption for a 300-liter/3 kW ESWH with XL tapping profile and standard charging***




### *Power (kW)* and energy storage (kWh*) capacity*

The desired hot water demand defined in the tapping profile can be provided from ESWHs with different combinations of tank volume, storage temperature and power capacity. ESWHs for residential use usually have a power range of 1–3 kW. For a given power range, the storage capacity depends on the tank volume and storage temperature. The storage capacity is approximately 14 kWh for a 200-liter tank with a 2 kW heating element (heated from 10 °C to 70 °C), and approximately 21 kWh for a 300-liter/3 kW ESWH.[2]

Smaller water heaters with less storage capacity require a heating element with a higher power rate and/or more frequent charging and/or higher temperatures to cover the same hot water demand. With less storage capacity it is more likely that the heating element is charged more frequently than with a larger tank. Thus, smaller ESWHs can be less flexible in their power demand than ESWHs with larger storage volumes.

## 2.2 How can ESWHs provide flexibility?

In order to change the charging profile of the ESWH, it must be possible to control the power element in the water heater based on a signal. When receiving a signal, the ESWH responds in less than a second.

The ESWHs can be controlled with various degrees of complexity, from a simple relay to advanced smart control systems. Demand-side management of ESWHs for system use has historically been obtained by ripple control. In ripple control a high-frequency control signal is transmitted via the power grid. When the unit receives the high-frequency signal, the load is switched off. Controlling the devices through ripple control gives the system operator a direct control over the customer's appliances. A smarter control of the ESWH can be achieved by installing an electronic thermostat with a controller. With smart control the customer can allow the unit to be controlled automatically by local optimization or remotely by a third-party. An ESWH is 10-20 per cent more expensive with a smart control system installed.[3] Smart control can also include two-way communication where it is possible to observe the state of the ESWH and whether it is on or off, increasing the control precision.

The tank temperature can be raised temporary to add energy content to the tank as a flexibility measure.[4] This requires a thermostatic controller where the setpoint change can be activated, as well as a mixing valve diluting the hot water supplied to the end user to avoid scolding. A higher temperature in the tank will incur somewhat higher heat losses, depending on the required tapping

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[2] Source: OSO Hotwater, assuming source water temperature of 10 °C
[3] Source: OSO Hotwater
[4] The hot water temperature in ESWHs in Europe is often limited to 55 °C due to calcareous groundwater, but the damage would be minimal if a temperature increase is rare.

pattern. According to the current Ecodesign regulation (EU) No. 814/2013 and the test standard EN 50540, ESWH with 'smart control' can get an efficiency bonus. 'Smart control' includes adaptive control that lowers the tank temperature when the ESWH is not in use over a longer period of time. This type of smart control lowers the energy content for flexibility of the typical ESWH by up to 50%. However, the impact of a change in the temperature setpoint on the flexibility potential is outside the scope of this report. The assumptions on the availability of flexibility provision from ESWHs are based on previous studies.

Standard ESWHs are either off or charging at full power capacity. There is no technical limit to how often the power element can be switched on and off nor any technical requirements for intermittent resting period. Thus, ESWHs are flexible loads with short latency and high cyclicity, this is a clear distinction to other technology types used for water heating. ESWH can operate both by reducing and increasing the consumption, depending on the charging state, without directly affecting the user. Manufacturers can implement electronic modulation or stepwise charging through multiple elements for adjustment of power use if there is a market for such functionality. Such functionality may however significantly increase the costs of the ESWH.

### *Load management strategies*

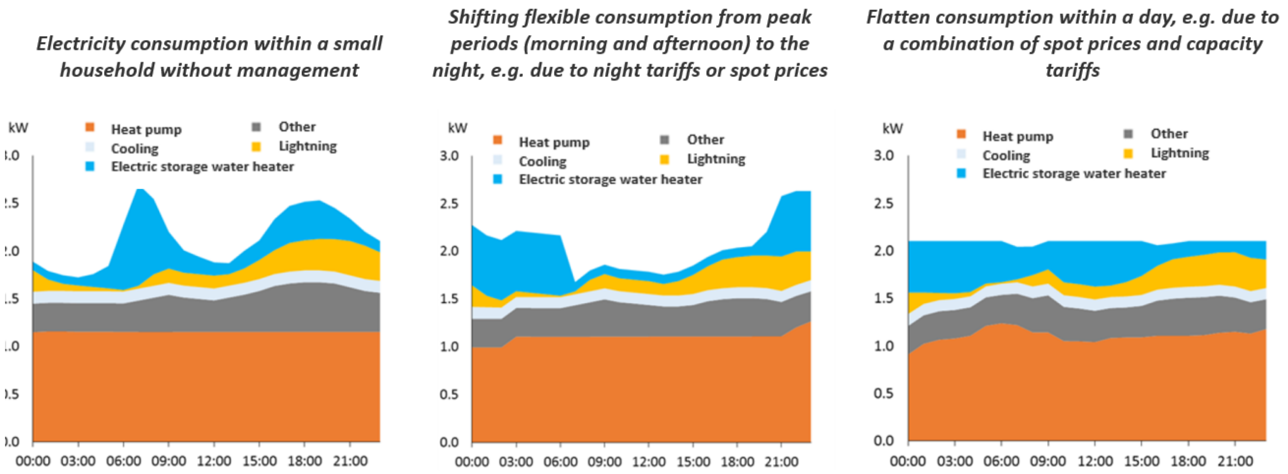
The technical characteristics of ESWH as a flexible resource enables different strategies to control the ESWH to deliver various types of flexibility.

- *Load shifting:* The charging of an ESWH can be shifted to a desired time period. The user profiles and the storage capacity (cf. Figure 1) suggest that it is possible to shift the charging profile significantly without any loss of comfort to the users (desired hot water supply). Load shifting can for example be achieved by preventing the power element from starting in high price periods.
- *Flattened energy consumption**:*** The energy consumption within a time period (kWh/h) can be reduced with an intermittent operation of the power element where the charging period is doubled by turning it on and off for shorter time periods. Alternatively, the consumption can be flattened by reducing the charging power (kW) if possible.
- *Fast regulation***:** The ESWHs can react fast if given a signal and can operate both up and down making ESWH suited for fast regulation.

In a report about the flexibility in the Nordic electricity market, Statnett (2018)[5] has calculated the maximum response a small household can provide without loss of comfort. The resulting flexibility with two different load management strategies are shown in Figure 2. The figure shows that, if not controlled, the ESWH contributes to the peak load of the household in the morning and the afternoon, and that it represents a significant flexible load if controlled.

[5] Flexibility in the Nordic power market 2018–2040. Analysis report. (In Norwegian.)

***Figure 2: Examples of load management strategies and response of ESWHs***



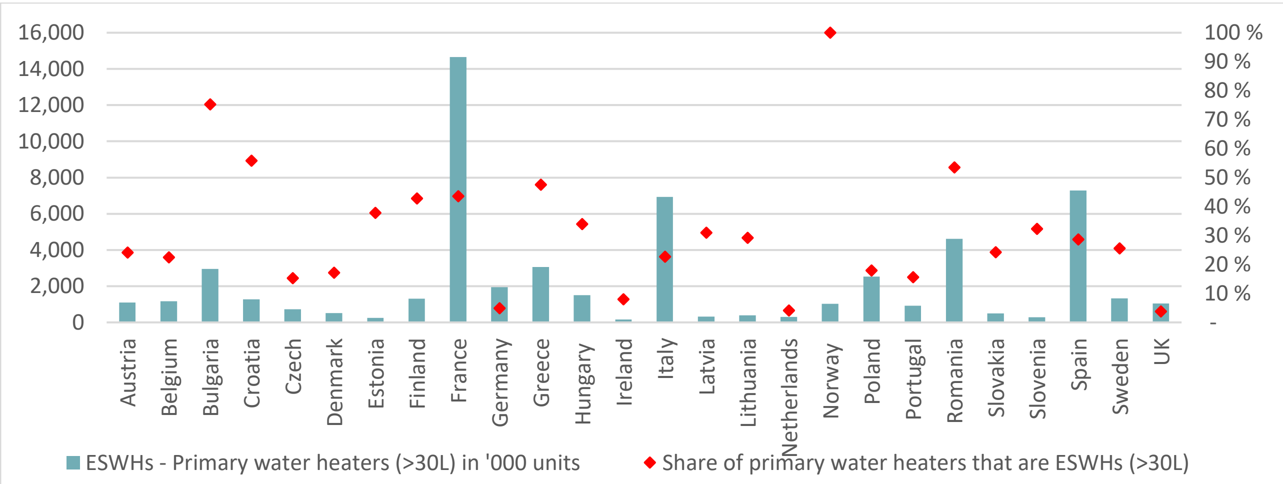

*Source: Statnett (2018)*

## 2.3 Mapping of flexibility potential from ESWHs in Europe

In addition, the total amount of flexible capacity of ESWHs in an area is determined by the prevalence and characteristics of the ESWH stock and their grid connectivity. Water heaters are installed in virtually all buildings. However, not all water heaters are heated by electricity, and electric dedicated water heaters include both electric storage types (ESWHs) and electric instantaneous types (EIWHs) without the storage ability and hence limited flexibility. The electric dedicated water heaters are located in the low voltage grid (230V- 400V). Thus, ESWHs in Europe represent extremely distributed flexibility source in the electrical energy system, but the prevalence of ESWHs in Europe varies between countries.

An overview of the stock of ESWHs (columns) and the share of ESWHs (diamonds) in the dedicated primary water heater park in European countries are presented in Figure 3.

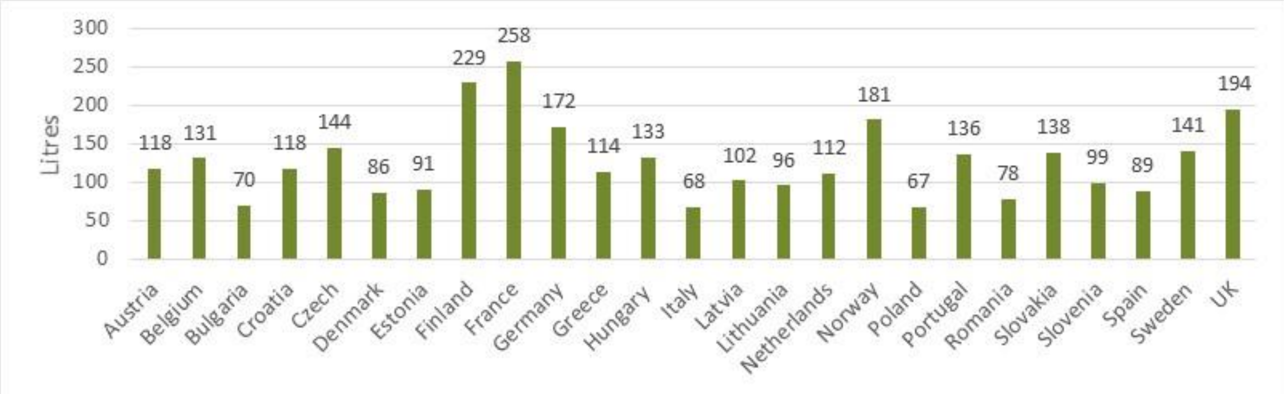
***Figure 3: ESWHs in the primary water heater park per country (2014)***




*Source: European Commission/VHK (2019) and Multiconsult (2017)*

Primary water heaters are the main, central water heaters in a building. In addition, a household can have secondary water heaters which are smaller water heaters with storage tanks less than 30 litres. Electric water heaters with larger storage capacity are more flexible than ESWHs with smaller storage volumes. Hence, our estimated flexibility potential is based on the primary water heater park. The average volume of primary ESWHs (storage capacity >30 litres) in the EU is 147 litres. From Figure 4 it can be seen that France and Finland have the largest average volumes.

***Figure 4: Average storage volume of ESWHs >30 L per country (2014)***




*Source: European Commission/VHK (2019*

ESWHs with historically traditional thermostats (bimetal) have an average lifetime of 15–30 years, while an electronical thermostat has an expected lifetime of 6-11 years. The stainless-steel tanks for pressurized water supply (>8 bar) used in typical ESWHs in Norway have an average lifetime of 20–30 years and more when used with the normal Norwegian water supply, very slightly acidic surface water. Typical warranty periods for the stainless-steel tank are at least 10 to 12 years.

### *Total flexibility estimates*

In France, 80 % of the 15 million ESWH units deliver flexibility to the electricity network by active demand-side management via an adapted tariff offer using ripple control. The 11–12 million managed units represent an annual energy consumption of 25 TWh and an installed capacity of 18 GW, of which approximately 50 % can be shifted each day, providing a daily flexible capacity of 8–9 GW and a controllable daily storage capacity of more than 50 GWh.[6]

The numbers from France can be used to estimate the flexibility potential in the EU. As the average volume for primary ESWHs in all of EU is 147 liters, while it is 258 in France, the available capacity per ESWH in the EU is assumed to be 40 % lower than in France. The 57 million ESWH units in the EU (from Figure 3), assuming 80 % contribute with demand-side management and 50 % of the consumption can be shifted, there is a potential of 20 GW of daily flexible capacity and a controllable daily storage capacity of more than 120 GWh from Electrical Water Storage Heaters in the EU.[7] A daily flexible capacity of 20 GW from ESWHs in the EU corresponds to a third of the nuclear capacity in France or the entire installed capacity of Czechia. The daily controllable storage capacity corresponds to the total storage capacity of the batteries of 3 million Nissan LEAF EVs.[8]

The flexibility potential from ESWHs estimated in this report is a theoretical potential assuming that the units can be controlled when available. We do not have data on the share of ESWHs that are currently controlled or equipped with smart control.

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[6] EDF position paper on review studies for Ecodesign and ecolabelling regulations for water heaters and storage tanks (2020)
[7] Calculation: $57\ million\ units\ in\ EU * 80\%\ controllable * 8.5GW\ daily\ flexibility * 60\%\ availability / 11.5\ \ million\ controlled\ units\ in\ France = 20\ GW$
[8] Based on the standard Nissan LEAF from 2020 with 40 kWh battery.
https://www.nissanusa.com/vehicles/electric-cars/leaf/features/range-charging-battery.html


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# 3 FLEXIBILITY BEHIND THE FUSE

*The energy transition changes household load patterns. Notably, induction hobs, more electrical heating, high pressure washers, some heat pumps without soft start and electrical vehicle (EV) charging implies higher peak loads, and roof-top solar PVs imply a demand for storage when household generation exceeds household consumption. While EV charging can provide flexibility as well, the interaction with ESWHs can provide additional flexibility at a low cost, in particular during evening peak hours. By storing excess PV generation as hot water, studies show that self-consumption can increase as much as 60 percent. Thus, ESWH flexibility and storage can interact beneficially with EV and PV behind the fuse, indirectly also reducing the need for grid capacity expansion.*

Relevant changes in consumption patterns in residential buildings include use of energy efficient but power consuming appliances like induction hobs, electrification of transport and the installation of EV charging and installation of roof-top solar panels. Both trends imply that the customers' load pattern and maximum load increases. These changes may translate into higher demand for grid capacity but may also be managed by flexible charging "behind the fuse". In this section we describe how utilisation of a flexible ESWH unit can be used for load shedding and shifting within the users' main fuse. For a prosumer, shifting the charging pattern of its ESWH can balance own production and give better utilization of in-house energy resources.

Figure 2 (see section 2.2) shows that the ESWH electricity consumption can be a major contribution to the morning and evening peak consumption within a household, but also illustrates that it is a very flexible load that can be used to shift load away from peak load hours.

## 3.1 Use cases

In order to illustrate the value of ESWH flexibility and storage behind the fuse, we describe two relevant use cases: co-optimization with EV charging with EV charging and utilization of in-house distributed energy production from PV. In addition, ESWHs can also interact with other (stiff) loads.

### 3.1.1 Interaction with electric vehicle charging

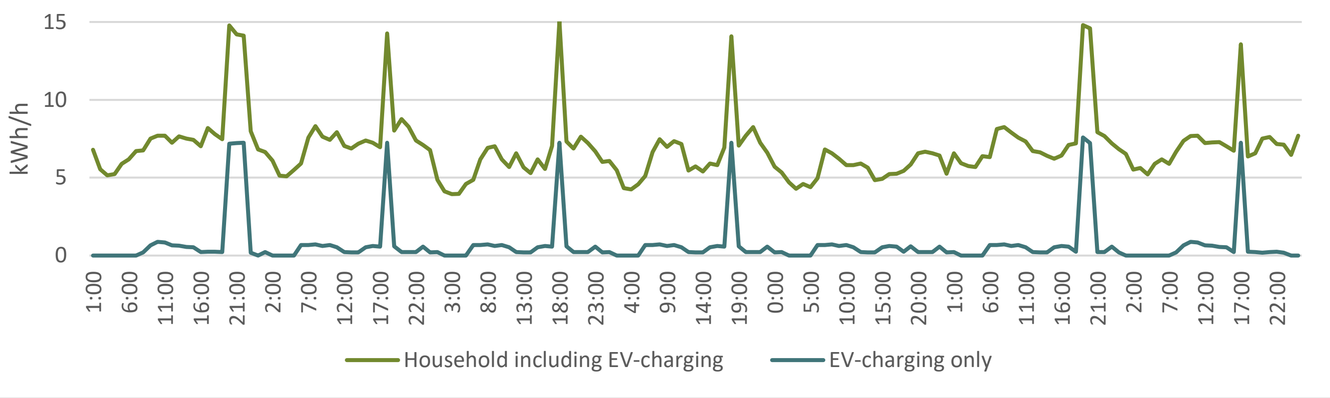
Unrestrained EV charging at home can significantly increase peak consumption within the household, especially since charging when returning home would increase the common "afternoon peak" in household electricity consumption. The power level of EV chargers ranges rather widely, where the residential charger typically is between 3.3 kW and 7 kW but can go up to 22 kW for three phase fast chargers. For consumers wishing to use higher power levels for charging at home, upgrades of the connection with the local grid are often required.[9]

ESWH can interact with EV charging as ESWH "charging" can be shifted in order to make room for EV charging at times when the ESWH would normally also be charged. Thereby, a consumer with an ESWH can install EV charging without having to increase the maximum capacity by the upgrading the grid connection and fuse size.

An example of a consumption profile for a Norwegian household with a 7kW EV charging can be seen in Figure 5.

[9] Amsterdam Roundtable Foundation and McKinsey & Company, The Netherlands 2014, Electric vehicles in Europe: Gearing up for a new phase?

***Figure 5: Hourly consumption in a week for a large Norwegian household with EV-charging***




According to this profile, the main EV charging for the consumer occurs 4-6 times a week in the evening, increasing the peak load by 7 kW up to 15 kWh/h. The peak load contribution of the EV charging depends on the capacity of the EV charger. Assuming the EV charging coincides with hot water consumption, the peak load can be reduced by shifting the reheating of the ESWH to later in the evening when the EV charging has completed. With a 3 kW ESWH the peak load could be reduced from 15 kWh/h to 12 kWh/h. With enough storage capacity in the ESWH the load can be shifted without loss of convenience to the user. Another possibility is to shift or reduce the capacity of the EV charging but this option may be more restricted due to user characteristics, i.e., involve a greater degree of inconvenience. Controlling the charging of the ESWH and the EV can be combined to flatten the consumption with minimal loss of convenience to the user. Thereby, the consumer can install EV charging avoiding electrical upgrades.

### 3.1.2 Interaction with PV generation

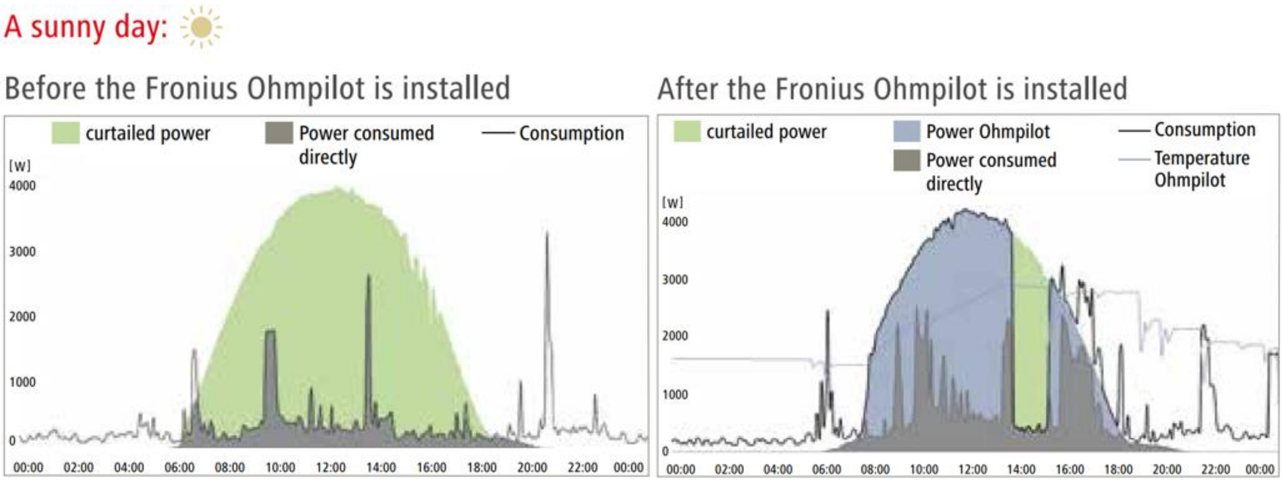
Instead of feeding excess PV generation into the grid, e.g. on sunny summer days when electricity consumption is low, the PV electricity can be used to heat water in the ESWH water tank instead of having to be curtailed due to insufficient feed-in capacity in the grid or excess system power supply.

Fronius, an Austrian technology company, has launched a consumption regulator designed to use excess solar power to heat water. The product, called Fronius Ohmpilot is optimizing self-consumption of PV generation through intelligent control of heating elements, including hot water storage tanks. Solar power can thus provide a family home with average water consumption with most of their hot water during spring and summer.

According to Fronius, the result is maximum self-consumption, a reduction in the household's $CO_2$ footprint, and less wear on the building's main heating system during the summer months.[10] Figure 6 illustrates how installation of a Fronius Ohmpilot can reduce curtailment of excess PV generation by using it in the water heating system instead. Fronius claims that the consumer's self-consumption can be increased to over 60 % by heating water with excess solar energy as illustrated in the figure below.

[10] https://www.fronius.com/en/solar-energy/installers-partners/technical-data/all-products/solutions/fronius-solution-for-heat-generation/fronius-ohmpilot/fronius-ohmpilot

***Figure 6: Illustration of how the Fronius Ohmpilot reduces curtailment of PV generation***




*Source: www.fronius.com*

Avoiding energy curtailment has both private and socioeconomic value as the resource do not go to waste.

## 3.2 Evaluation

The interaction between ESWHs as a flexible storage facility and other loads and resources behind the fuse can reduce the maximum capacity, and hence the necessary fuse size and grid connection capacity for a household. Interaction with distributed generation can increase self-consumption of renewable energy. The reasoning also suggests that ESWH provides a flexibility potential for local energy communities and within smaller grid areas where resources are aggregated and shared locally.

The flexibility giving benefits behind fuse could also be provided by alternative solutions, such as other flexible loads, e.g. heat pumps and EVs and others energy storage solutions such as batteries installed behind the meter. In the future electricity system such local flexibility solutions are expected to all contribute to the balancing of local systems, and to be optimized according to the specific situations and system demands.

If the end-user or prosumer can avoid increasing the fuse size when installing new energy efficient power consuming appliances, EV charging or solar panels, this implies that an additional value accrues to the grid company since it reduces the maximum load of the consumer (due to load shifting and storage). Flattening the load profile may also reduce the balancing cost of the DSO and TSO. In several countries part of the grid tariff is based upon the size of main fuse in the building, to keep the main fuse as low as possible but as high as necessary in order to avoid electricity faults and overheating of the electrical components, is an imperative motive.

The value of the flexibility from ESWHs behind the fuse is not quantified here as most of the value of reduced peak load is likely to accrue to the grid company. This is not to say that if will not be attractive for end-users to charge ESWHs flexibly. Benefits can accrue to the end-user in the form of control systems installed by aggregators, enabling energy savings, and/or through reduced grid tariffs or remuneration for flexibility services rendered to the distribution or transmission grids. Such remuneration or tariff reductions should however reflect the value of increased quality and security of supply for the grid companies. The value of flexibility from ESWHs for the electrical power system will be covered in the following chapters.

# 4 FLEXIBILITY IN THE LOCAL DISTRIBUTION GRID

*Different flexibility resources, if used in a grid-friendly manner, can contribute to reduced investment costs in distribution grids. ESWHs have the necessary characteristics – well defined storage, high cyclicity, short resting time – to provide all the relevant distribution grid flexibility services: voltage control, grid capacity management, and congestion management. By aggregating several ESWHs and ESWHs and other sources of demand side flexibility, studies show significant potential cost savings. The value of ESWH as a flexibility resource depends on the cost of alternatives, ranging from investments in grid elements, including storage, batteries, EVs, heat pumps and other demand-side flexibility, and distributed generation. DSO markets for flexibility are in their infancy and current market prices are weak indicators of the value of flexibility for DSOs. Different battery solutions have comparable characteristics as ESWH and probably provide the best basis for assessing the alternative value of flexibility from ESWH.*

While flexible loads such as ESWHs can provide benefits to the individual grid customer in terms of avoided costs related to fuse size and connection capacity, larger benefits of demand-side flexibility are likely to be realized in the distribution grid.

Historically, the need for electricity infrastructure has grown in tandem with economic growth. The focus of distribution companies has been to expand grid capacity accordingly. With ample capacity in distribution grids and ample flexible generation in the central system, the balancing of the system has been the responsibility of system operator. Now, a number of trends changes this logic:

- *Grid capacity expansion is less economic*: Peak load increases more than energy demand due to energy efficiency advances and technology development, reducing the utilisation rate of grid capacity in general, and of new grid capacity in particular, thus increasing unit costs. The trend to increasingly require underground cables instead of overhead lines, especially in urban areas, also imply increased unit costs for grid capacity expansion.
- *Loads can be used to balance the system:* New technologies make it possible to exploit consumer flexibility at lower cost. Individual and small loads can be automatically controlled. Maximum peaks can be managed by other means than ample capacity margins or rationing.
- *Connection of distributed generation:* Increased distributed generation poses new flow patterns and new challenges in the operation of distribution grids.

In addition, ambitious climate policies have increased the uncertainty in demand forecasting. As stated in an analysis by Carbon Trust (2016)[11] "the need to invest despite uncertainty creates the possibility for regret, where decisions turn out to be suboptimal and have long-lasting negative consequences." Actively using flexible resources can be used as a 'least-worst regret' solution. While traditional grid investments are costly and non-reversible decisions, demand flexibility can offer a safer path until the uncertainty is resolved. Moreover, "(a)dditional flexibility can also provide 'option value', whereby small investments in flexibility can postpone decision-making on larger investments until there is better information, hence reducing the need to make potentially high regret decisions."

Massive investments are expected in European electricity grids in the decades to come. The European Energy Industry Investments report 2020[12] refers to projections in World Energy Outlook (2014) and EC Energy Roadmap 2050. Both imply that infrastructure investments will increase and that the bulk (75 % plus) of needed investments relate to distribution infrastructure. According to the Roadmap, the biggest share of the costs for distribution is related to "upgrade and extension of distribution networks and the development of smart grids". In the most likely and feasible scenarios,

[11] An analysis of electricity system flexibility for Great Britain, Imperial College London
[12] https://www.eesc.europa.eu/sites/default/files/files/energy_investment.pdf

estimates vary from 40 to 50 % increase in annual investment needs above 2011-2020 levels. Clearly, if these costs can be contained by smart use of cheap flexibility resources, the benefits can be substantial. This is also a rationale for the interest in flexibility solutions such as batteries and in the establishment of aggregators, and in the EUs emphasis on engaging consumers in the electricity market and facilitating the participation of aggregators in different markets. Mechanisms for the use of flexibility resources and demand-side management in distribution grids are currently not wide-spread, although several different studies and pilots have demonstrated potentials, possible technical solutions, and the extent to which consumers respond to different price schemes.

## 4.1 Use cases

In order to assess the potential value of ESWH for local distribution grids, we first describe relevant use cases and then go on to estimate the costs of alternative solutions.

We distinguish between three typical use cases for flexibility in distribution grids, based on the categorization in a report by CEER (2020)[13].

- *Voltage control*, where demand-side flexibility is used to manage power quality issues
- *Grid capacity management*, where demand-side flexibility is explicitly taken into account in network planning, i.e., the use of demand-side flexibility is planned as part of normal grid operation
- *Congestion management*, where demand-side flexibility is used to manage temporary network challenges that are either planned or unforeseen.

The challenges have different characteristics which translate into characteristics that the resources providing the flexibility services must exhibit in order to represent a relevant alternative to grid expansion. An overview is shown in Table 1.

***Table 1: Flexibility characteristics relevant for DSOs***

| | Characteristic | Description |
|---|---|---|
| *Time dimension* | Time period | What time of the year, day(s) of the week, hours during the day? |
| | Response time | How predictable is the issue and how fast must it be solved? Does it happen at certain temperature levels, or is it impossible to predict? How quickly must flexibility respond to solve the challenge? Can one be notified a day / hour before, or must the shutdown be instantaneous? |
| | Frequency | Is the issue happening often? Or does it happen very rarely, e.g. only in unusual network error situations? |
| *Volume* | Capacity | How much capacity fixes the problem? How big is the voltage challenge? |
| | Energy need / duration | How long does the grid issue last? Minutes, hours or days? |
| *Location* | Where do the challenges occur? | Where in the grid is the issue located? How does the flexibility response affect the surrounding grid environment? |

### 4.1.1 Voltage control

Voltage control is essential for the quality of electricity supply. Electric appliances are designed to work within a limited voltage bandwidth around 230/400 V and may be damaged if the voltage is higher or lower. Voltage quality may be challenged by feed-in of distributed generation in the

[13] CEER Paper on DSO Procedures of Procurement of Flexibility

distribution grid, with problems typically occurring when generation from distributed RES significantly exceeds demand (CEER, 2020). The challenges typically occur when there are substantial and fast flow changes and when the total loads on a line or in a grid area approach the capacity limit.

Voltage control in weaker radial distribution grids with a low short-circuit capacity is particularly important to maintain the expected lifespan of electric and electronic devices. The roll out of Advanced Metering Systems (AMS) in distribution grids allows for a much better surveillance of power supply quality. While measurement of end-user power supply quality previously would require that experts install calibrated and certified measuring instruments at the end-user, this is a functionality of the smart meter devices currently rolled out as required in EU regulation.[14] The regulatory push for market-based mechanisms and access for new service providers also means that end-customer data on power supply quality becomes available. As voltage deviations can now be monitored automatically and continuously, one can expect that the focus on voltage quality in distribution networks will increase.

Voltage challenges and absorption of reactive effect must be handled in real-time grid operation and requires devices that can provide fast and automatic response. The voltage level can be too high or too low, hence, depending on the situation, adequate voltage control requires resources for both up- and down-regulation. Moreover, voltage control is largely a local issue, i.e. resources for voltage control must be available in different parts of the grid.

ESWHs exhibit the necessary characteristics to contribute to voltage control: They can react fast, the response can be automated, they can provide up- and down-regulation, and they represent a highly distributed resource (cf. description of characteristics in chapter 1). ESWHs ability to provide fast response is also well demonstrated by the fact that ESWHs are already used as flexible providers for frequency containment which also requires automatic and very fast response (see next section).

#### 4.1.2 Grid capacity management

Flexibility can play a role in grid planning and be used to defer grid investments. If the DSO can rely on the availability of flexibility resources, grid expansions can be deferred or avoided without compromising safe operation of the grid. Traditional measures to manage increased demand are to precautionary increase grid capacity and to maintain ample capacity margins. Without the technology and metering to access and control individual loads, such precaution has been necessary to maintain reliable electricity supply. If the grid is not able to accommodate peak loads from consumption and/or distributed generation the system will be overloaded. To avoid outages in such cases, the traditional fall-back option is rationing or disconnection of grid customers.

Even when there is a gradual increase in demand, the grid capacity will only be constrained in a few hours during high load periods. In areas where demand mainly comes from residential buildings, peak load typically occurs for a few hours in the morning and a few hours in the afternoon. Thus, grid constraints are relatively predictable and securing access to load shifting resources in these hours can reduce grid costs. For the DSO to be able to plan grid developments with less capacity by considering flexibility as an alternative, the flexibility resource must be reliably available in times of system stress. More energy efficient devices may lead to shorter bursts of high power demand, e.g. induction hobs or electric instantaneous water heaters (EIWH). The grids have to be dimensioned to tackle these power peaks. The remaining time the grids are less utilized, meaning there will be increased times with idle capacity at higher costs.

ESWHs represent a flexible resource for load shifting and energy storage, a characteristic that is demonstrated in the control of ESWH charging through “Ripple control” load management, already implemented in Finland and France for decades. The load profiles for ESWH show that, if not controlled, they will be charging exactly in the hours when diurnal demand is peaking, i.e. adding to

[14] Annex I to the Electricity Directive 2009/72/EC requires the EU Member States to roll out electricity smart meters to 80 % of consumers by 2020, unless the result of a Cost Benefit Analysis (CBA) is negative.

the load that determines the dimensioning of grid capacity. Their flexibility characteristics however imply that this demand can be shifted from peak hours with no or very little loss in comfort for the consumer. In addition, if controlled, ESWH can readily provide flexibility in other timeframes as well, e.g., help store surplus generation from distributed generation if the grid is constrained.

### 4.1.3 Congestion management

Even when the grid is planned with ample capacity (n-1), scarcity and congestion situations can occur. Sometimes these situations are planned some time ahead, for example maintenance work on the grid, connection of distributed generation, or other infrastructure projects such as transport, district heating or gas. Reductions in grid capacity due to planned maintenance is usually clarified weeks and months in advance. Thus, activation of demand side flexibility for these situations can also be clarified in due time. Normally, flexibility to reduce or disconnect load will be necessary for high-load periods, as the total grid capacity is not fully utilized in most hours of the day.

In addition, if demand grows more rapidly than forecasted there might not be sufficient time to invest in increased grid capacity. Thus, by using flexible resources, new loads can potentially be connected to the grid earlier. Normally, new loads are not given access to the grid until the grid capacity is considered sufficient, alternatively, pending grid investments, new connection is offered a contingent connection contract. Contingent connection implies that the load can be disconnected if there is a risk of overload on the system. If the new loads are not very flexible such a contingent connection contracts may not be attractive, however. If the DSO has access to other flexibility resources that can shift load, however, more loads can be connected unconditionally.

Finally, unforeseen overload or fault incidents are likely to occur from time to time, and the risk of such incidents may increase with increased intermittent generation and more capacity-intensive consumption in distribution grids. Unforeseen events must be solved as or after they occur. In these cases, it must be possible to activate demand-side flexibility on short notice. Thus, arrangements for the activation of flexibility must however be clarified beforehand in order for the option to be available when the incident occurs.

Again, ESWHs has the characteristics necessary to provide load shifting for several hours every day and is also a fast resource. Thus, the flexibility of ESWHs can potentially contribute security of supply and efficient grid operation in all of these situations.

## 4.2 Alternative values

In general, flexibility can save grid investment costs and potentially provide benefits in terms of earlier connection of new loads. Utilizing such flexibility is economical when alternatives are cheaper than grid investments or less expensive than the value of early connection of new loads. In general, expansion of the capacity of the network itself (cables, lines and substations) is the most expensive option to accommodate increased power demand in the grid (peak load). As explained above, however, due to changes in load patterns and grid costs, in addition to the increased uncertainty pertaining to electricity demand projections, we expect that the business case for grid capacity investments will become weaker in many cases. This implies that distribution companies will be looking for alternative, more economic solutions to manage peak load situation and other grid challenges.

Demand side flexibility is one of the options which has become all the more attractive due to smart metering and technology advances and supported by the emergence of new service providers and aggregators. We therefore expect various flexibility solutions to be relevant alternatives when the business case for grid expansion is uncertain or clearly uneconomical. For the distribution grid company, the subsequent question is what other solutions are available, and their cost, reliability, location and time characteristics. So, although the alternative value of demand-side flexibility is ultimately to defer grid investments, ESWHs are but one possible provider of flexibility. Thus, in order to assess the potential value of the flexibility provided by ESWHs for the distribution grid, we focus on the cost of other alternatives than grid capacity expansion in the form of lines and substations.

The main categories of possible alternatives to flexibility from ESWHs as a flexible DSO resource are

- Demand-side response from other sources
- Distributed generation
- Investments in flexible grid components

Distributed generation is more likely to be the source of challenges in distribution grids due to its variability and intermittency, although to the extent to which the generation can be operated flexibly, it cannot be ruled out in some situations.

### 4.2.1 Alternatives to ESWH flexibility

As discussed above (in section 4.1), flexibility is valuable for three main purposes in distribution grids. The use cases require different characteristics and can thus be provided by different sources. The main alternatives for the use cases are:

*Voltage control*

The quality of electricity supply (voltage control) requires fast and frequent automatic response and is generally maintained by requiring automatic response such as mandatory balancing bids from central generation units and by investment in integrated network components including storage, installed at relevant locations in the grid. In addition to such traditional grid measures, demand-side flexibility from other sources than ESWHs, batteries, and distributed generation could potentially contribute to voltage control in the distribution grid. A clear advantage of ESWHs, is that they are capable of delivering both immediate up- and down regulation, and that they are an extremely distributed flexibility resource. Another advantage compared to demand-side loads related to heating, such as electrical heating and heat pumps, is that they are available in summer periods when voltage levels can be challenged due to low loads.

*Grid capacity management and congestion management*

Grid capacity management requires load shifting, facilitated by storage. Largely the same characteristics are needed for congestion management. The main difference in business cases for grid capacity management and congestion management, is that, since grid capacity management implies the planned use of flexibility in normal grid operation, congestion management is by definition a less frequent challenge. This implies that solutions not requiring specific investments, i.e. that are already available, are more attractive for congestion management.

Load shifting can be provided by simple peak shaving (turning off electric appliances) or by storage solutions such as ESWHs, heat pumps with storage, and batteries, including EVs. Modern heat pumps with water storage are highly flexible and can provide load shifting and storage comparable to ESWH – as with ESWHs, the heating up period can be adapted, and the pump is flexible in terms of varying the power load down to the minimum load (approximate 20-30 % of maximum load). Heat pumps can be controlled by signals from the grid. Heat pumps are not designed to be switched on and off with a high cyclicity and short resting time. If the heat pump is frequently shut down it will harm the compressor lifetime, but heat pumps can be switched off for an hour our two every day. Hydronic heat pumps are however potentially less distributed than ESWH, as they are more commonly used in buildings with hot water infrastructure for space heating.

In meshed grids, congestions will often be handled through changes in network topology. Generally, however, unless there are ample capacity margins in the grid, topology changes are likely to increase the risk of reduced quality of supply and even outages or rationing. This risk increases if the grid is planned with low capacity margins, which is likely to be the case in the future due to the trends and new possibilities described above. On radial connections or in less meshed grid areas, topology changes may not always be possible.

### 4.2.2 Value estimates

We conclude that overall, batteries have characteristics that are most comparable to ESWHs and that other demand-side flexibility can contribute as well. Usually, alternative values, especially when there are several different sources of the service or good in question, and when the values are related to multiple characteristics, will be reflected in market prices. Markets for flexibility in distribution grids are however not yet widely developed. While we have looked at prices observed in pilots and existing markets, we also estimate the alternative value of ESWHs by comparing them to the costs for batteries providing corresponding services.

#### System level value estimates

A study by E-bridge (Özalay et.al. 2019)[15] concludes that by using flexibility in a grid-friendly manner, the investments needed to integrate new loads in Germany until 2035 can be more than halved, representing total savings of almost €20 bn. Taking into account the cost of flexibility and additional ICT infrastructure needed for grid diagnosis, activation and steering of flexibility services, the annual savings exceed 40 %. The cost savings depend on the share of the flexibility that is used in a grid-friendly manner, as opposed to only responding to wholesale market prices.

In addition, flexible loads and storage can increase the efficiency of RES integration: the study finds that RES curtailment can be reduced by 65 % in 2035. Finally, flexibility on lower grid levels can provide benefits at higher grid levels as well. The study includes RES, electrical vehicles, heat pumps, small-scale storage and other loads in households, the service sector and industry.

It should be noted that the study expects the flexibility potential from space heating, electrical vehicles and small-scale storage to increase substantially in the future. Even though ESWHs are not widespread in Germany, the study indicates the substantial potential value of using distributed flexibility in distribution grids.

Frontier (2017)[16] also studied how flexibility can reduce operational costs of distribution networks in Germany (redispatch) and found that the maximum realistic potential for upregulation in 2023 is 10 GW, while the potential for downregulation is 40 GW, notably with available flexibility being much higher in high load hours. They assume that the cost of using demand-side flexibility for both up- and downregulation corresponds to the difference between peak and off-peak prices, estimated at 26 €/MWh (reflecting a higher marginal value of electricity consumption during peak hours). Alternatives include biomass, CHP, wind and PV generation. While the cost of increasing generation from biomass and CHP is estimated at 65 and 60 €/MWh, respectively, with wind and PV only able to provide down-regulation, also with substantially higher costs than load shifting.[17]

The estimates thus indicate that the alternative value of demand-side response (load shifting) is in the range of 34–39 €/MWh.[18]

#### Prices in GB DSO flexibility markets

There are few, if any, examples of mature markets for DSO flexibility. In Europe, Great Britain is a notable exception, although even here DSO markets for flexibility are still in their infancy. While market prices and alternative values are likely to vary from country to country (and indeed from DSO to DSO), the GB prices can still serve as indications.

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[15] Özalay, Schuster, Kellermann, Priebe and Moser (2019): Wirtschaflicher Vorteil der netzdienlichen Nutzung von Flexibilität in Verteilnetzen. (In German.)
[16] Frontier Economics (2017): Beitrag von Flexibilitäten im Verteilnetz zur Senkung der Redispatchkosten in Deutschland. (In German.)
[17] The study holds that both biomass and decentral CHP can reduce generation at zero cost.
[18] Comparing the cost of increased generation (60-65 €/MWh) with the cost of DSR (26 €/MWh) the numbers indicate that the marginal net value of using DSR is 34–39 €/MWh.

*Overview*

All of Britain's local electricity grid operators have committed to include the use of smart flexibility service markets when considering the building of new electricity network infrastructure. The commitment covers all new relevant projects "of significant value"[19], where local electricity operators face congestion in high voltage grid infrastructure that results from increased electricity demand and from distributed energy projects being connected to the grid.

Flexibility services are expected to play a big part in avoiding the need for expensive reinforcement as the network seeks to accommodate growth in low-carbon technologies, thereby helping to keep costs down for customers. In 2020, a total of 1900 MW of flexibility has been tendered by British DSOs, a significant increase compared to 2019.

The British DSO flexibility markets are being developed. In April 2020, a common agreement established a set of standard products for the procurement of flexibility services by all the DSOs. The four standard products are:[20]

- Sustain Service, used to manage peak demand loading on the network and pre-emptively reduce network loading. The requirement windows for provision of these services will be scheduled and fixed at the point of contract.
- Secure Service, used to manage peak demand loading on the network and pre-emptively reduce network loading. Secure requirements are declared week-ahead each Thursday for the following week (commencing Monday). Payments consist of an Arming fee which is credited when the service is scheduled, and a further utilisation payment awarded on delivery.
- Dynamic Service, developed to support the network in the event of specific fault conditions, often during summer maintenance work. As the service is required following a network fault, it consists of an Availability and Utilisation fee. By accepting an Availability fee, participants are expected to be ready to respond to Utilisation calls within 15 minutes. Dynamic availability windows are declared week-ahead each Thursday for the following week (commencing Monday).
- Restore Service, intended to help with restoration following rare fault conditions. Such events are rare and offer no warning as they depend on failure of equipment. Under such circumstances, response can be used to reduce the stress on the network. As the requirement is inherently unpredictable, Restore is based on a premium 'utilisation only' service. This will reward response that aids network restoration but will pay no arming or availability fees. Participants declared available for the Restore Service will be expected to respond to any utilisation calls within 15 minutes and will receive an associated utilisation fee.

Below we describe the products and prices offered by the British DSO Western Power Distribution as of September 2020, when different DSOs still procured different products and different prices and price structures. Western Power did however procure the Secure, Dynamic, and Restore services.

The prices used for the calculation below must be seen as an illustrative example. As the markets are not yet fully developed and the values are likely to vary between locations and across seasons, we cannot say to what extent the prices reported by Western Power in September 2020 are representative.

*Value estimate*

For each network area with capacity constraints, Western Power will buy flexibility to reduce or handle the constraint. The 'Restore' product supports power restoration in the case of a fault. The 'Secure' product provides flexibility to manage peak demand, while the 'Dynamic' product is used in the case of maintenance work or other predictable fault conditions. By the end of 2019, Western

[19] As far as we know, "significant value" is not defined in detail.
[20] Source: https://www.flexiblepower.co.uk/about-flexibility-services


THEMA Consulting Group
Øvre Vollgate 6, 0158 Oslo, Norway
www.thema.no

Power had contracted 123 MW of flexibility in total. This covered almost 70 % of their expected flexibility need.[21]

As of now, Western Power sets a fixed price for flexibility contracts. In the future, they aim to set the price using an auction or even generate close-to-real-time pricing using short-term demand and supply. Table 2 provides an overview of the price structure as of September 2020.

***Table 2: Western Powers pricing of flexibility products***[22]

| | Arming | Availability | Utilisation |
|---|---|---|---|
| *Secure* | £ 125 / MWh | | £ 175 / MWh |
| *Dynamic* | - | £ 5 / MWh | £ 300 / MWh |
| *Restore* | - | - | £ 600 / MWh |

*Source: Western Power Distribution*

So far, flexibility has only been procured to manage capacity constraints in the high-voltage network. The next step for Western Power Distribution will be to consider using flexibility to handle voltage disturbances in the low-voltage network. It is not known whether the set-up for flexibility products for managing voltage disturbances will differ from the set-up to handle capacity constraints.

Based on the contracted capacity of 123 MW (Western Power Distribution), the value of the different products can be estimated at

- *Secure*: The total annual value is estimated at 12 million €, corresponding to appx. 110–160 €/year for each ESWH. The market is mainly used to contain the afternoon peak on weekdays throughout the year, estimated to 520 h and with an average activation time of 45 minutes.[23]
- *Dynamic*: The total annual value is estimated at appx. 1.1 million €, corresponding to 9–14 €/year for each ESWH. The market is used to manage the grid during fault situations and summer maintenance. We have assumed that the market is activated for 56 h throughout the year, with an average activation time of 30 min each time.[24]
- *Restore*: The total annual value is estimated at appx. 1 million €, corresponding to an annual value of 7.5–12 €/year for each ESWH. The market is used to support the grid during rare fault situations. We have assumed that the market is activated 24 h per year and for 30 minutes each time.[25]

For the estimated values of individual ESWHs, the range reflects that the power of the ESWHs are 2 or 3 kW. Moreover, we have assumed that each ESWH is activated 50 % of the relevant hours. With these assumptions, you would need between 82.000 and 123.000 ESWHs to cover the need for 123 MW of flexible capacity.

The assumed activation frequency and the duration of activation is highly uncertain and may be over-estimated. On the other hand, the 50 % utilization rate may be on the low side.

If the ESWH participates in all markets and is activated according to the estimates above and the prevailing prices, the flexibility from an average ESWH represents an annual value of 125–190 €/year. This is likely to be a high estimate in today's grid situation but may be more representative in a future with more peaky demand and lower capacity margins.

[21] The network companies are working to increase the supply of flexibility to make sure that there are sufficient flexibility resources available to handle future network constraints.
[22] The arming fee is credited when the service is scheduled, while by accepting an availability fee, participants are expected to be ready to respond within 15 minutes when called upon to deliver.
[23] In the description of the product it says that the service is expected to be needed for the evening peak on weekdays throughout the year. We have assumed that the service is needed for 2 hours on all weekdays.
[24] Assuming flexibility on average is needed for 2 hours all 7 days of the week for 1 month (4 weeks)
[25] Assuming flexibility on average is needed for 2 hours once in each month (12 times)


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### Stockholm flex

The Stockholm region in Sweden is experiencing grid capacity challenges in the regional grid. In winter 2020, an R&D project in the Stockholm region, sthlmflex, will test a flexibility market in the region. The project is a cooperation between Svenska Kraftnät (TSO), Ellevio (DSO), Vattenfall (DSO) and NODES (market operator). Three different flexibility products will be implemented locally, differing in location, notification time, duration, auction design and pricing, and bid sizes, and includes mFRR. The flexibility can be provided through aggregation of resources.

The project has estimated that the Stockholm region typically needs 13–18 GWh of flexibility during mild and normal winters, and more than 75 GWh during particularly cold ones (on average occurring every 10th year). In mild and normal winters, flexibility reserves will be activated in approximately 200 different hours, giving an average flexibility need of 65–91 MWh/h.[26] In a cold winter the reserves are used in nearly 700 different hours which puts the average flexibility need per hour of activation at 107 MWh.

For illustration, the estimate implies that the average hourly flexibility need in the Stockholm region can be covered by between 43.200 and 107.000 ESWHs, depending on the average size of the aggregated ESWHs and how cold the winter is. The illustration assumes that the average size of an ESWH is between 2 and 3 kW and that 50 % of the total capacity is available to provide flexibility during the relevant hours. For reference, there are 460.000 households in Stockholm municipality and roughly 1 million households in Stockholm county. If we assume that 200.000 single dwellings have water heaters, access to 20 % of the ESWHs could be sufficient to provide the entire flexibility need in mild and normal winters.[27]

As the sthlmflex project has just been launched and is a demonstration project, hence, no prices or costs are available yet. The results from the project will at best provide a basis to assess the potential for demand response and the costs involved, but it will still be too early to expect that the project will provide solid evidence of the value of ESWHs and demand response as a local flexibility resource for the future, although the situation in Stockholm may be an early example of capacity challenges in an urban area that may become more prevalent in cities across Europe in the future.

### Characteristics and cost of batteries

Apart from demand-side flexibility based on electric appliances in buildings, batteries emerge as the alternative with characteristics most similar to ESWHs. Both batteries used for e.g. EV charging and dedicated battery packs can provide flexibility to the grid. An advantage with battery packs is that they can be provided in different sizes depending on the flexibility need of the system or location.

A Norwegian research project mapping the potential for flexibility from charging of EVs found that 90 % of respondents were willing to postpone charging from day/afternoon to night (21.00 to 05.00) if the shift did not have any negative consequences. In an FRR pilot carried out by Norwegian TSO, Statnett, in which flexibility from EV chargers were offered by an aggregator, a guaranteed reserve of 0.25 MW was offered from an 80–90 EV portfolio, with a response time of 2 seconds. Access to the reserve was best at night.

Below we refer to studies of different batteries that are likely candidates to provide distributed flexibility in distribution grids.

The market for batteries is currently dominated by Li-ion batteries. Other battery chemistries are starting to become competitive for different kinds of applications:

- *Heavy-duty mobility*: Solid-state batteries, such as zinc alkaline, Li-metal and Li-sulfur

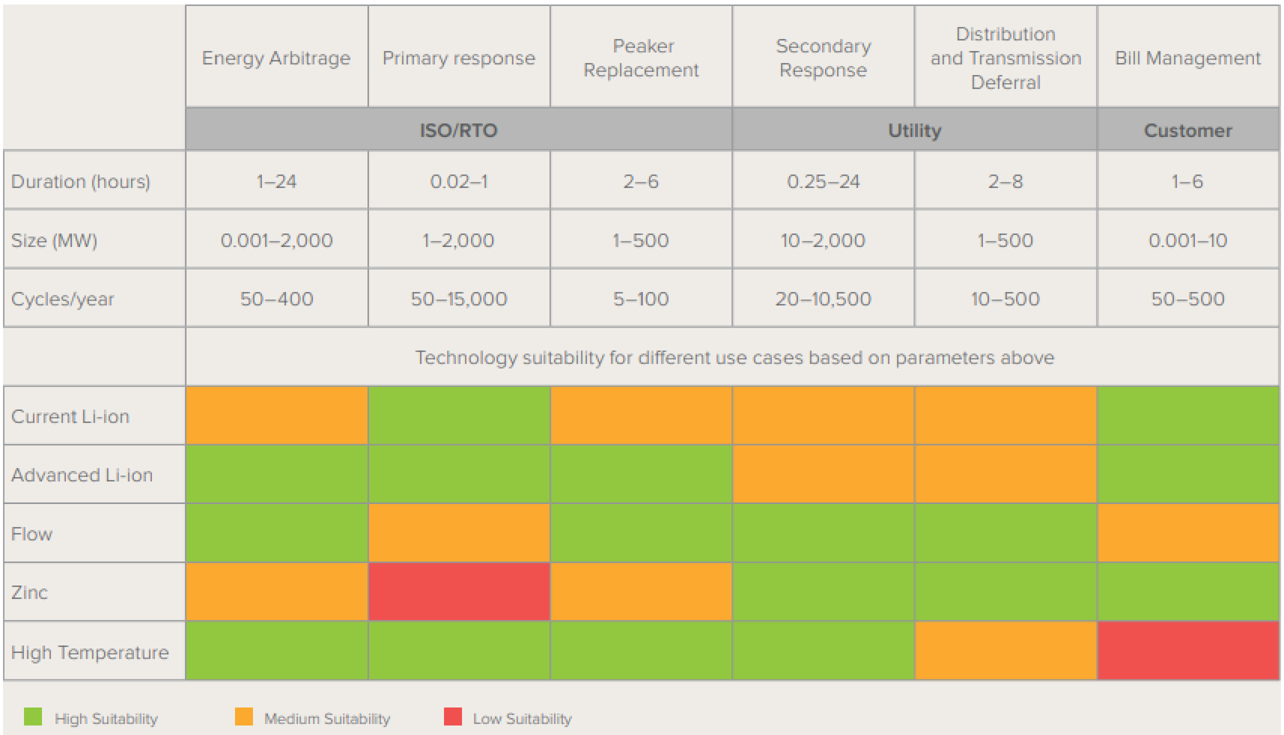
[26] 13-18 GWh per 200 hours equals 65-91 MWh/h.

[27] Ten percent of households in Stockholm municipality live in single-family houses. We assume that the share is higher in the greater Stockholm area. It should also be noted that there is a high share of district heating in Sweden.

- *Grid balancing:* Chemistries categorised by low-cost and long-duration, such as zinc-based, flow and high-temperature
- *Enable fast charging and increasing share of EVs:* High-power batteries

All battery technologies listed above are suitable for different grid applications. Figure 7 illustrates the suitability of each technology for a selection of use cases.

***Figure 7: Battery technology suitability for different use cases***



| | Energy Arbitrage | Primary response | Peaker Replacement | Secondary Response | Distribution and Transmission Deferral | Bill Management |
|---|---|---|---|---|---|---|
| | ISO/RTO | | | Utility | | Customer |
| Duration (hours) | 1–24 | 0.02–1 | 2–6 | 0.25–24 | 2–8 | 1–6 |
| Size (MW) | 0.001–2,000 | 1–2,000 | 1–500 | 10–2,000 | 1–500 | 0.001–10 |
| Cycles/year | 50–400 | 50–15,000 | 5–100 | 20–10,500 | 10–500 | 50–500 |
| | Technology suitability for different use cases based on parameters above | | | | | |
| Current Li-ion | | | | | | |
| Advanced Li-ion | | | | | | |
| Flow | | | | | | |
| Zinc | | | | | | |
| High Temperature | | | | | | |

High Suitability Medium Suitability Low Suitability

*Source: Bloch, Newcomb, Shiledar, and Tyson (2019)*

While current Li-ion batteries are best suited for provision of primary response, i.e. frequency containment and voltage control, advanced Li-ion batteries are also well suited for energy arbitrage and peak replacement services.

The table also defines the different use cases in terms of the characteristics needed, such as energy arbitrage requiring durations of 1-24 hours (storage), capacities ranging from 1 kW up to 2000 MW, and 50-400 cycles per year.

Lazard (2020) contains cost data for different batteries that are suitable for three different use cases:

- *Transmission and Distribution*: Batteries intended to mitigate transmission or distribution upgrades. Such batteries are intended to provide flexible capacity and maintain grid stability.
- *Wholesale:* Large battery systems intended to meet several needs, including frequency regulation and wholesale market participation.
- *Commercial and Industrial:* Behind-the-meter batteries intended for peak shaving and reduction of grid fees for commercial and industrial energy users but can also be used for DR participation and in local capacity resource programs.

Assessed technologies and their costs in the different use cases are presented in Table 3 and Table 4. The cost estimates based on nominal capacity (MWh) depends on the use case, i.e. the number of hours that the battery is used in the different applications.

***Table 3: Breakdown of LCOS for battery capacity for different use cases, EUR/MWh***

| *Use cases* | Trans-mission and Distribution | Whole-sale | Commercial and Industrial |
|---|---|---|---|
| *Capital costs* | 1 546-2 115 | 67-128 | 264-361 |
| *Charging costs* | 59-80 | 49-93 | 139-190 |
| *O&M costs* | 240-329 | 15-28 | 10-14 |
| *Other costs* | 390-533 | 16-30 | 65-88 |
| *Tax costs* | 94-129 | 5-9 | 18-25 |
| *LCOS* | 2 329-3 187 | 152-288 | 497-679 |

***Table 4: Breakdown of LCOS for battery storage capacity, EUR/kW-year***

| *Use cases* | Trans-mission and Distribution | Whole-sale | Commercial and Industrial |
|---|---|---|---|
| *Capital costs* | **230-314** | 28-173 | 131-178 |
| *Charging costs* | 9-12 | 20-126 | 69-94 |
| *O&M costs* | 36-49 | 6-38 | 5-7 |
| *Other costs* | 58-79 | 16-30 | 32-44 |
| *Tax costs* | 14-19 | 2-12 | 9-12 |
| *LCOS* | 346-474 | 63-391 | 246-336 |

Source: Lazard (2020)

It emerges that if we assume that the battery capacity is only used for grid capacity management (fast response), the levelized cost of storage amounts to 346–474 €/kW/year, of which capital costs are estimated to 230–314 €/kW/year (66 %). Thus, if we assume that a 2 kW ESWH provides the same services as a battery, where the ESWH *capacity* is already available and does not entail dedicated investment, using the ESWH can save investments in battery capacity of 460–628 €/year. In order to replace the services from a 10 MW battery, however, the control of 5.000 ESWHs is needed. The estimated cost per stored energy unit (the volume of shifted energy) is very high for uses in transmission and distribution grids due to a low number of activation hours.

The cost of using batteries for load shifting is better represented by the battery cost estimates for wholesale and commercial and industrial use. The same battery (pack) can probably be used for more than one use case, but the values cannot simply be aggregated as, for example, battery capacity cannot be used simultaneously for wholesale and transmission and distribution purposes, i.e., as for ESWHs, the total value is reduced by simultaneity.

The cost estimates in Table 3 and Table 4 are based on a range of assumptions, both general and technology specific, including the following:

- Project lifetime: 20 years
- Capital structure: 20 percent debt at an 8 percent interest rate, 80 percent equity at a 12 percent return on equity.
- Tax rate: 21 percent
- After tax WACC: 10.9 percent, results from capital structure and tax rate
- Exchange rate EUR/USD: 1.15

### Summary of estimates

The estimates reported above are summarized in Table 5 on a per kW basis. The estimates are not readily comparable, as they are estimated based on different use-cases and for different markets. We do however observe that:

- The value estimates based on prices in the Western flexibility markets are not market-based and the markets and products are still being developed. On the other hand, the assumptions we have used, may overestimate the value of flexibility in the markets. The values are however also based on just one set of prices, and we know that prices vary by location, by DSO, and by season.
- The estimates based on battery costs are however strikingly substantially higher than the estimated values in the GB market. Battery costs are however set to be reduced, and the value of flexibility expected to increase in the future.

***Table 5: Alternative value estimates for flexibility provision in DSO networks***

| | Power €/kW/year |
|---|---|
| ***Flexibility market prices*** | |
| *Western Secure market (GB)* | 110 |
| *Western Dynamic market (GB)* | 9.2 |
| *Western Restore market (GB)* | 7.8 |
| ***Cost of alternatives*** | |
| *Battery cost system stability* | 346–474 |
| *Battery cost wholesale market* | 63–391 |
| *Battery cost behind-the-meter* | 246–336 |



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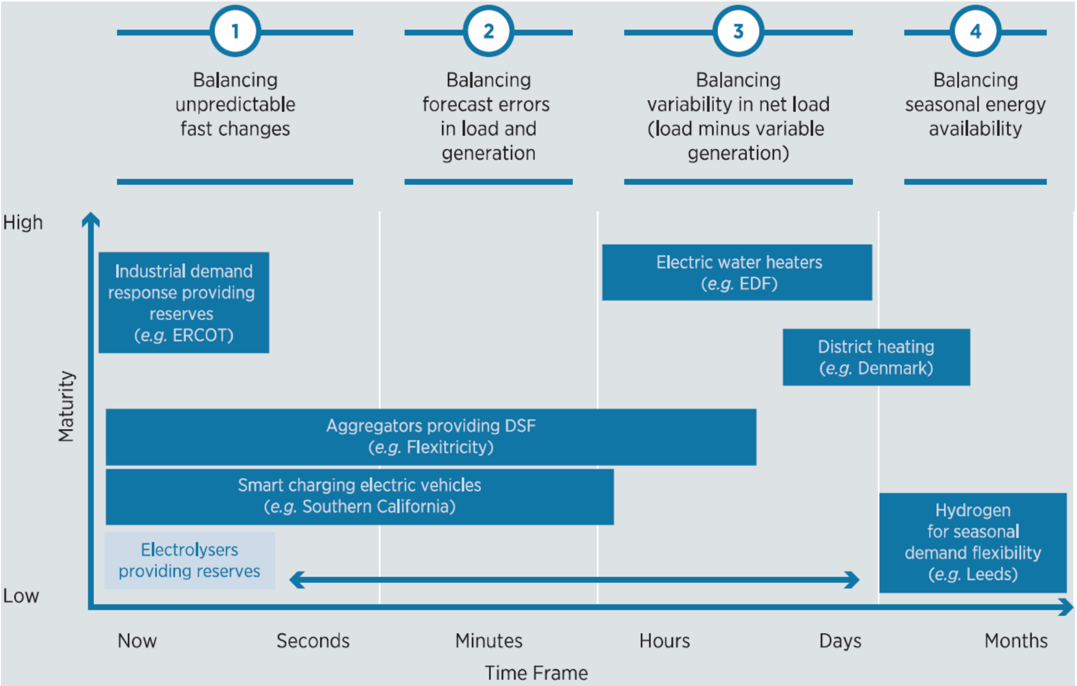
# 5 FLEXIBILITY IN SYSTEM OPERATION

*Electrical storage water heaters are already aggregated and used by system operators for provision of frequency control and to balance electricity supply and demand during peak hours. In addition, the potential flexibility value has been demonstrated in several pilots. The value of flexibility, and the most beneficial type of flexibility, does however vary substantially with the specific system characteristics. In France, for example, the value of ESWHs is generally regarded as providing the highest value as a source of down-regulation of energy consumption in peak load hours, reducing the need for investments in peak plant capacity. In general, however, the need for demand-side flexibility in system operation is expected to increase.*

In addition to the values that demand-side flexibility can provide to the distribution grids, it can also contribute to the system operation of transmission grids. Electricity production and consumption must be balanced at all times in order to avoid blackouts and maintain supply quality. The flexibility needed by transmission system operators in thermal power systems has traditionally been provided by large thermal power plants, or in hydro-based systems as Norway, by the rotating machinery in hydroelectric power pants. Increasing shares of intermittent renewable energy and reduction of synchronous thermal generation results in loss of inertia and increased imbalances in thermal systems, triggering increased need for balancing and ancillary services by the system operators. More flexibility is needed as the amount of inflexible production for renewable energy increases, making demand-side flexibility increasingly relevant. This also applies to systems with a high degree of production from hydroelectric power plants, as particularly fast frequency flexibility induces wear and tear that is avoidable with aggregated DSM resources. There are currently multiple examples of flexibility from ESWHs being used for system operation across Europe, and the flexibility in power demand from water heaters has already been used for balancing in the power systems in Finland and France for several decades.

Demand-side flexibility can contribute to meet the flexibility needs in all time frames of operation of the electrical system, as illustrated in Figure 8. ESWHs are particularly suited for the time frames from immediate response to short-term storage within a day for balancing variability in net load.

***Figure 8: Demand-side flexibility real applications classified by maturity and time scale***




*Source: IRENA (2019)*[28]

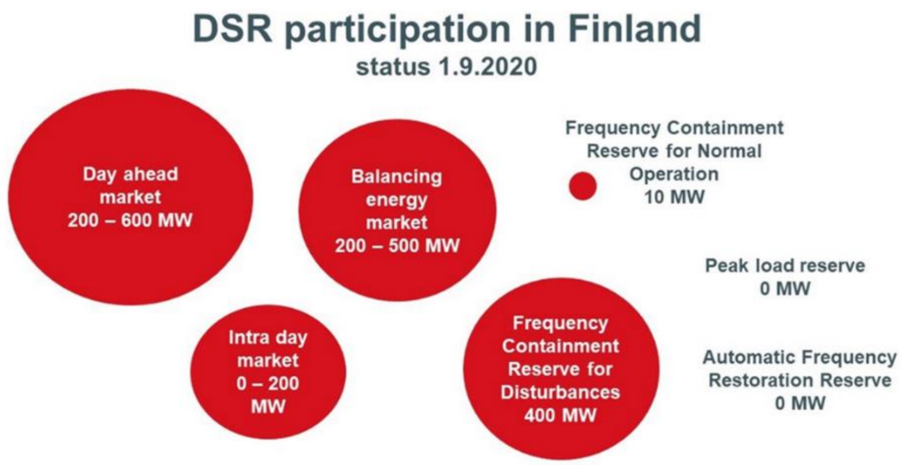
The faster demand-side flexibility services, e.g. for the balancing of unpredictable fast changes and forecast errors in load and generation, will usually be provided through an aggregator in an unbundled power market. Due to market design features and transaction costs, aggregation and aggregator services may be necessary in order to make use of local and small-scale flexibility resources.

Today, demand response can participate as peak load reserve and in some balancing markets. However, the participation of demand response in other markets is limited due to restricted access or large minimum bid size due to national regulations and systems not adapted to cater for aggregated flexible consumption.

In Finland, electricity consumption has long been used as a reserve for maintaining the power balance. Fingrid, the Finnish TSO, considers demand-side management as an opportunity to increase supply in both regulating power and reserve markets. Demand-side flexibility is participating in the same marketplaces as electricity production. Historically, demand-side flexibility has been provided by large industry and via ripple control of residential loads including electric water heaters, but Fingrid reports increasing interest from aggregators who aggregate small-scale consumption. Fingrid has experienced reduced market prices as new providers such as independent aggregators or suppliers have entered the markets lately. The status of the demand side flexibility used for balancing and regulation in Finland is shown in Figure 9.

[28] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Dec/IRENA_Demand-side_flexibility_2019.pdf

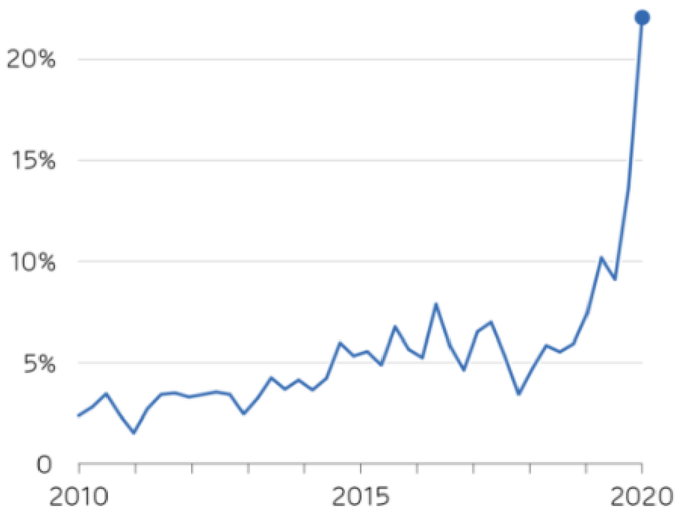
***Figure 9: The use of demand-side response (DSR) in the Finnish market***




Source: Fingrid (2020)[29]

The demand for flexibility in system operation in Europe is increasing as the amount of inflexible production of renewable energy increases. In 2018, the share of energy from renewable sources in gross final energy consumption reached 18 % in the EU. The increase in the share of renewables is essential to reach the EU climate and energy goals and is planned to further increase rapidly. The EU's target is to reach at least 32 % by 2030. Figure 10 shows how balancing prices in the GB have developed since 2010. The yearly increase in the price since 2010 is due to the share of variable renewables (Drax Electric Insight, 2020). However, the peak in balancing cost per MWh in 2020 is also affected by lower than usual energy demand due to the corona virus. A study performed by Imperial College London shows that for every extra percent of electricity supplied by wind and solar, 10 pence (approx. 11 cents) per MWh are added to the balancing price, which is illustrated in Figure 11. (Drax Electric Insight, 2020). The increasing need for flexibility makes demand-side flexibility, including flexibility from ESWHs, more relevant.

***Figure 10: The quarterly-average cost of balancing the power system, expressed as a percentage of the cost of generation***




Source: Drax Electric Insight (2020)[30]

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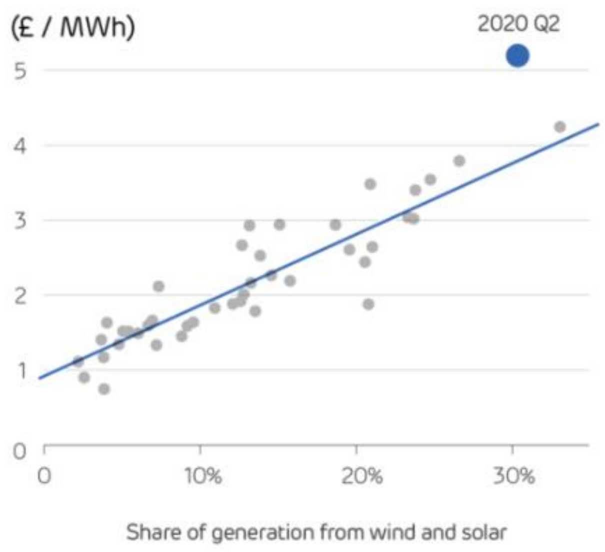
[29] https://www.fingrid.fi/en/electricity-market/market-integration/the-future-of-the-electricity-markets/demand-side-management/
[30] https://www.drax.com/energy-policy/the-cost-of-staying-in-control/

***Figure 11: Balancing price shown against share of variable renewables, with dots showing the average over each quarter***



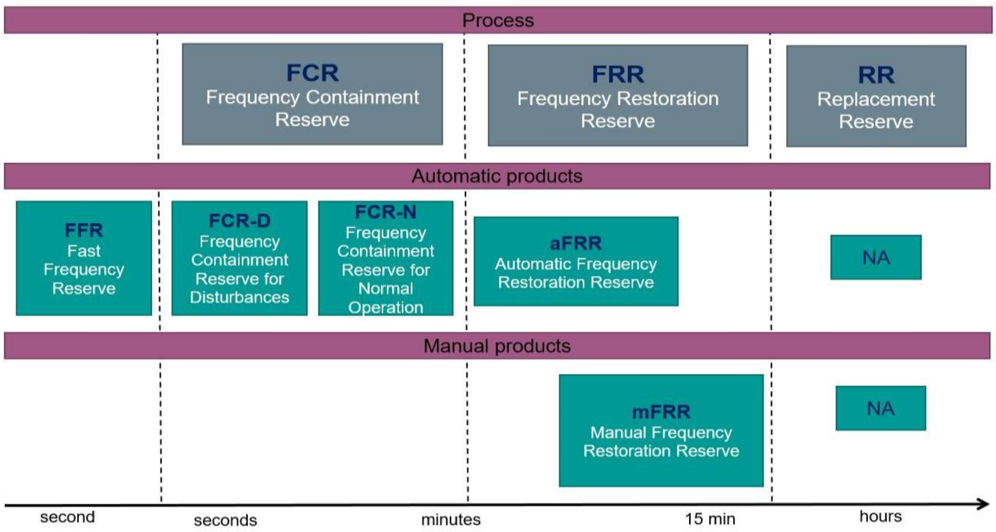

Source: Drax Electric Insight (2020)[31]

Below, we describe some examples of use cases for the provision of flexibility services from ESWHs to TSOs.

## 5.1 Frequency control

Electricity production must be equal to electricity consumption at all times. The balance between production and consumption is indicated by the frequency of the electricity grid which has a nominal value of 50.0 Hz. In order to manage imbalances, the system operator must have sufficient and relevant reserves for different purpose and timescales. An overview of the frequency reserve process and the related reserve products is given in Figure 12.

***Figure 12: Frequency reserve process and products***




Source: Fingrid (2020)[32]

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[31] https://www.drax.com/energy-policy/the-cost-of-staying-in-control/
[32] https://www.fingrid.fi/en/electricity-market/reserves_and_balancing/#reserve-products

Further specifications of the different frequency reserve markets in the Nordics is given in Table 6.

***Table 6: Rules and specifications of different frequency reserve markets in the Nordics***

| | **FFR*<br><br>Fast Frequency Reserves** | **FCR-D Frequency Containment Reserves - Disturbance** | **FCR-N<br><br>Frequency Containment Reserves - Normal** | **aFRR<br><br>Automatic Frequency Restoration Reserve** | **mFRR (RKM)<br><br>Manual Frequency Restoration Reserve** |
|---|---|---|---|---|---|
| *Bidding deadline* | D-1 | D-2, D-1 | D-2, D-1 | D-2 | D-1 |
| *Minimal bid* | 1 MW | 0.1 MW | 0.1 MW | 5 MW | 10 MW,<br>1 MW for some BSPs |
| *Up-/down-regulation* | Up-regulation only | Up-regulation only | Symmetric, asset must be able to provide equal amounts of up- and down-regulation | Up- and down-regulation | Up- and down-regulation |
| *Activation criteria* | Frequency below 49.7 Hz | Frequency below 49.9 Hz | Frequency deviation of less than 0.1 Hz | Frequency deviates from 50.00 Hz | Frequency deviates from 50.00 Hz, to relieve activated aFRR assets |
| *Response time* | 1.3 s at 49.7 Hz, 1.0 s at 49.6 Hz, 0.7 s at 49.5 Hz | 50 % within 5 seconds, 100 % within 30 seconds | 100 % activation within 3 minutes | 30 s,<br>100 % activation within 120 s | 15 minutes |
| *Compensation* | Capacity: Clearing price (€/MW, h) | Capacity: Pay-as-bid on activated assets | Two parts:<br>• Capacity: Pay-as-bid<br>• Energy: Clearing price (up or down) on net energy provided during activation<br>Asset also compensated for production imbalance caused by automatic activation | Capacity: Same pricing as mFRR | Determined by marginal units. Could also be determined from spot prices in bidding zones. |
| *The rules and specifications may not be representative for each individual country. The Nordic TSOs are currently working on establishing common balancing markets. This is called the Nordic Balancing Model (NBM). *Based on the market solution used by Fingrid.* | | | | | |

*Source: Fingrid, Statnett*

All TSOs in Europe maintain Frequency Containment Reserves (FCR) and Frequency Restoration Reserves (FRR). In addition, some TSOs in the EU maintain Restoration/Replacement Reserves (RR), but RR is not used in the Nordic Power System. Fast Frequency Reserve (FFR) has been used in the Nordics since 2020. The reserve contributes to frequency containment in low inertia situations, typically occurring during summertime, with low production from rotating machinery with high inertia, combined with high renewables generation and flows on HVDC interconnectors.

The FFR and FCR reserve must respond automatically within seconds of activation and last for up to a few minutes. FCR-N is used for up and down regulation of either production or load within the 50 Hz +/- 0,01 band. ESWH can respond to a signal from a system operator or an aggregator and in a matter of seconds increase or decrease load depending on the need. This makes ESWHs suited for fast frequency regulation and for both up- and down regulation, which is also the main service from demand-side management of ESWHs today. Smart grid enabled ESWHs may also react automatically to frequency and voltage deviations based on preset values.

Demand-side management of ESWHs can also be relevant for slower frequency reserves if large numbers of ESWHs are aggregated ensuring necessary capacity and duration can be delivered, presuming demand-side response has access to the markets.

### 5.1.1 Real-life examples of aggregation for frequency reserves

There are several examples of 3rd party service providers aggregating ESWHs and other demand-side resources to provide frequency control to transmission system operators.

#### Voltalis

Voltalis has been providing distributed load shedding in France since 2009 and was the first aggregator in Europe to be approved for provision of balancing services.[33] The company's service is based on controlling consumer appliances remotely through a smart box that is installed in households and businesses. This enables Voltalis to aggregate capacity that is then offered in balancing and reserve markets. The business model implies that the smart boxes are installed and operated free of charge, while the benefit for the consumer is to be able to use the free application to access a detailed real-time overview of their electricity consumption. Voltalis' source of revenue is the value of participation in ancillary markets. The company currently controls appliances in more than 100 000 households. Assuming that every home has an ESWH with an average size of 2 kW, Voltalis could control more than 2 MW of capacity from ESWHs alone. In addition, Voltalis has access to ELSH Electric Local Space Heaters in the households.

According to EdF, there are in total more than 10 million homes in France with ESWHs. The total daily potential capacity of the water heaters in these homes is estimated to be 8-9 GW and more than 50 GWh, which could reduce the installed capacity of French nuclear power plants with 13 %.[34]

Voltalis currently operates at a regional level by selling capacity to the French TSO, RTE. This includes supplying Primary FCR.[35] Depending on whether ESWHs are controlled locally or remotely via internet, response times vary from less than a second to at most 10 minutes, with remote control having the slowest response time. Means can be taken to reduce the remote response times to around one second, well within the 30 second requirement for participation. Voltalis plans to extend its services to the local level (DSO) in the future.

#### Fortum Spring

Dubbed the largest "virtual battery" in the Nordics, Fortum Spring aggregates capacity from different flexible sources in Finland. These sources include 2100 ESWHs, Ericsson's data centre in

[33] Bivas (2011), https://www.ecole.org/en/1009/RT120111-ENG.pdf
[34] https://bilan-electrique-2018.rte-france.com/total-generation/?lang=en
[35] https://www.rte-france.com/actualites/rte-et-voltalis-developpent-un-nouvel-outil-de-flexibilite-pour-la-gestion-du-reseau


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Kirkkonummi in Southern Finland, and a battery pack in Kuru in Southern Finland.[36] The project has been operated since 2017.

The aggregation of assets with different properties makes the virtual battery suitable for short term balancing with fast response times. Response times can be less than one second, and in one pilot Fortum Spring demonstrated response times of less than two seconds with more than 1 MW of power. The current total demand response capacity in Finland is around 430 MW. According to Fortum, demand response and storage is expected to replace increasing volumes of hydropower in the faster reacting reserve markets (FFR, FCR), pushing hydropower into the slower reacting reserve markets.

The ESWHs included in the portfolio of Fortum Spring are currently only used to supply FCR-N services. According to Fortum, ESWHs could participate in the FFR markets if equipped with the appropriate control unit. ESWHs could also provide DR services locally on the DSO level, but no such market exists in Finland today. The project does provide services to the Finnish DSO Elenia, but only from the battery pack included in the virtual battery.

### tiko

tiko is a Swiss aggregator that develops demand flexibility solutions both in Switzerland and in neighbouring countries. Below are some examples of real-life use cases involving tiko's technology:[37]

- *direct energie, France:* On behalf of the utility direct energie, tiko developed a system to control heating systems in households remotely. The solution helps consumers gain insight into and reduce their electricity consumption.
- *EKS, Switzerland:* tiko has made a system used by prosumers to optimize self-consumption from their PV systems. The solution can optimize load patterns based on either profitability (tariffs and electricity prices) or self-consumption.
- *Repower, Switzerland:* tiko has aggregated capacities from household residences with electrical heating that are customers of the utility Repower. The aggregated capacity is offered to capacity markets.

According to tiko, ESWHs have several properties that make them preferable to conventional batteries for some uses, e.g. optimizing PV self-consumption. One such property is that ESWHs have virtually unlimited "charging cycles", another that ESWHs are already installed in most households, greatly reducing the need to undertake investments in order to make capacity available. tiko also connects to heat pumps, these are however used for longer time constants.

tiko uses ESWHs to provide FCR to TSOs today. The control units used by the company enable ESWHs to be switched on or off in less than five seconds, well below the 30 second requirement in the FCR markets serviced by tiko.

### Svenska kraftnät pilot

In 2017, Svenska kraftnät carried out a pilot project "Flexibla hushåll"[38], which aimed to test demand-side response for the automatic frequency-controlled reserve for normal operation, FCR-N. In the pilot, Fortum delivered approximately 0,1 MW frequency reserves to Svenska kraftnät by controlling the supply of ESWHs with average size between 2 and 3 kW in 90 households in the Stockholm-region. The pilot did however find that it would be necessary to aggregate a somewhat larger number of ESWHs (than the 90 included in the pilot) to ensure the minimum bid size. The ESWHs normally consume power less than half of the day. To ensure symmetrical regulation capacity for up and down regulation, half of the ESWHs were kept on to provide up-regulation, while the other half was kept off to provide down-regulation.

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[36] https://www.fortum.com/products-and-services/smart-energy-solutions/virtual-battery-spring
[37] https://tiko.energy/resources
[38] https://www.svk.se/siteassets/om-oss/rapporter/2017/slutrapport-pilotprojekt-flexibla-hushall.pdf


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The study concluded that if ESWHs are to supply services to the existing FCR-N market, Svk's ICT-system and market rules has to be adapted, and the quality of meter data needs to be improved.

### *Value estimates*

The FCR-N market compensates capacity (availability) according to pay-as-bid capacity reservation and for energy (activation) according to the clearing price on the net energy provided during activation. The energy compensation is highly dependent on the hour of activation. The average capacity price for FCR-N in Sweden was 17.04 €/MW/h in 2020.[39] This implies that a symmetrical bid of 0.1 MW every hour (equivalent to the capacity of 100 ESWHs with an average capacity of 2 kW available 50% of the time) will receive availability compensation of 14,927 €/year, corresponding to 75 €/year per kW of installed ESWH capacity with 50 % availability.

## 5.2 Capacity adequacy and balancing of supply and demand

In the above sections, we have focussed on the value of ESWHs as providers of flexibility in grid operation and balancing. The TSOs are however also responsible for the balancing of hourly demand and supply in the system if the market fails to equate the two. The increasing share of variable renewable energy sources – such as wind and solar – in the electricity mix leads to a growing need for backup generation capacity. Furthermore, this leads to shorter runtimes (load factors) for conventional power plants, some of which are only used in case of peaks in demand and may not be profitable because of limits as to how much electricity prices can rise in such cases. Demand-side flexibility, including ESWHs can be a valuable resource to avoid costly investments in peak load capacity.

In France, electric storage water heaters, by their storage capacity, are today the main lever for active demand management at low cost, controlling a daily storage capacity of more than 50 GWh and a flexible load of 8-9 GW, via an adapted tariff offer. The ESWH loads are shifted to reduce peak load and avoid peak load generation.[40] This equipment therefore offers flexibility in the electricity system which is extremely interesting to preserve, or even develop, to support the development of renewable energy.

### *Value estimates*

The cost of peak capacity reserves is estimated to 40 000-60 000 €/MW/year.[41] If an ESWH can provide an average flexible capacity of 1 kW, demand-side management of ESWHs to avoid peak load reserves have an estimated value for the system operation of 40-60 €/year based on investment costs alone. This is comparable to the estimated price differentials between peak and off-peak hours in Germany reported by Frontier (2017), which indicate a value of around 50 €/year. The latter estimate is based on the assumption that ESWHs are activated for downregulation four hours twice a day (during the morning and afternoon peak) and are available half of the days in the year. Note that this value can be realized via responses to wholesale market prices or through TSO market platforms.

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[39] https://mimer.svk.se/PrimaryRegulation/Submit

[40] EDF 2020, interview and position paper on review studies for ecodesign and ecolabelling regulations for water heaters and storage tanks

[41] Own estimate based on rough estimate of fixed gas turbine costs and costs of reserve capacity in Swedish bilateral agreements.

# 6 OVERALL ASSESSMENT AND OBSERVATIONS OF BENEFITS

## 6.1 System perspective

In the chapters above, we have described how the flexibility of ESWHs can provide value to the power system, by local balancing and interaction with local demand and local generation within a building (behind the fuse) or a local energy community; by deferring investments and reduce costs in the distribution grid; and in the balancing of the central energy system both in terms of energy balancing and system operation. There are several alternatives to the flexibility offered by ESWHs, but ESWHs have some very attractive characteristics:

- They are highly distributed, which means they can contribute to grid operation in areas with few alternatives
- They can respond fast and frequently to automatic signals with very low cost
- They do not represent extra investment costs
- The technology to control them is already demonstrated for a long time and in different contexts

While the flexibility of ESWHs can be a valuable resource for several purposes in the energy system, the full potential will not be available for all the purposes at the same time. Thus, the values for each service or system level cannot simply be aggregated. For example, if ESWHs are used to balance EV charging and PV generation in order to reduce the fuse size of a building, the likelihood that the ESWH is switched off during peak load periods increases. While, if used in this manner, they contribute to reduce peak load, and thus, indirectly the need for grid investments, they cannot simultaneously be switched off to provide up-regulation for the DSO's grid capacity management.

Similarly, if the ESWHs are used to manage congestion in the distribution grid, the resource will not be available for simultaneous supply of system services to the transmission grid. And if, as in France, ESWHs are used to balance system energy supply and demand, they cannot simultaneously be used for up-regulation in grid operation. This does however not mean that ESWH flexibility can *only* provide value in one part of the system, as the different challenges are not perfectly correlated.

In which part of the energy system and for which purposes it is most beneficial to use different flexibility resources depends on the characteristics, costs and location of different resources – and on the availability of sufficient alternatives. As ESWHs have fewer competitors in the distribution grids and, within distribution grids in radials, we expect that in general, a significant part of the value potential exists in distribution grids and, and in particular, in relation to radials or smaller grid areas where there are fewer alternatives and alternative costs are high. But as the examples show, ESWH flexibility can also provide substantial value on an overall system level, both in frequency balancing and in the management of peak load hours.

Currently, the prevalence of ESWHs differs substantially between countries and systems. In future, however, as the energy system is to be decarbonized and increasingly electrified, ESWHs can become an important substitute for water heaters operated on fossil fuels. Other zero-carbon alternatives to fossil fuelled water heater exist but requires technology development and infrastructure development (hydrogen) or changes in the building's energy infrastructure (hydronic heat pumps). Thus, the volume of ESWHs, and hence the flexibility potential, could increase in the future.

## 6.2 Barriers and facilitators

The analysis above indicates that the stock of ESWHs in Europe represents a substantial flexibility potential that may play a role in reducing the costs and facilitating the transition to a low-carbon energy system based on intermittent renewable energy and increased electrification of energy use.

ESWHs represent a distributed flexibility source where each unit generally has a relatively small capacity. The energy storage units can react individually to price signals from wholesale markets or grid tariffs. Such market price responses do on the one hand require that end-users are exposed to



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varying market prices and grid tariffs that reflect the capacity situation in the grid, and on the other that they have the information and technical equipment to be able to respond to the price signals. The roll-out of smart meters, the establishment of data hubs and the emergence of service providers, imply that the preconditions for efficient price response are developing. But to what extent consumers will take advantage of these possibilities remains to be seen. It is however reasonable to assume that propositions to use flexibility use from electrical loads that can easily be controlled without loss of comfort, will be more attractive to consumers. Economic theory as well as research on consumer behaviour indicate that consumers are more willing to provide flexibility if the costs in terms of changes in behaviour and comfort are low, and if they benefit in terms of remuneration or a lower electricity bill. Information and the ability to manually override controls signals may however also be instrumental.[42]

In order to utilize the flexibility potential from ESWHs (and other distributed resources) in the provision of system services to DSOs and TSOs, however, individual loads must be aggregated in order to contribute. For this to happen, aggregators must be given access to flexibility markets, and flexibility markets and adequate incentive schemes must be established. As the examples above demonstrate, aggregators do already participate in some of the TSO balancing markets. On the DSO level, flexibility markets are however in their infancy. Until the frameworks for participation is developed and the regulation of distribution networks are incentivized to utilize flexibility solutions when it is cheaper than grid capacity investments, it is hard to tell to what extent demand-side flexibility will be a competitive contributor and what the value is.

In summary, the efficient utilization of demand-side flexibility in general, i.e., to what extent the potential will be utilized and to what extent it will be exploited where it provides the most value, depends on the design of markets and incentive schemes, but also on the potential volume and costs of the flexibility potential. Based on the analysis presented in the chapters above, we believe that ESWHs, if properly incentivized, have properties that make them a very interesting source of flexibility in the distributed and renewable power system of the future.

[42] Ongoing research on these topics includes the Sintef Energy and Cicero project https://www.sintef.no/prosjekter/den_fleksible_forbruker_flexeffect/

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