Analysis of the European energy system under the aspects of flexibility and technological progress

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1 INTRODUCTION

The decarbonisation of the energy system is one of the main challenges that the European Union is facing in the coming years and decades. Achieving the targeted emission reductions of 80 to 95% compared to 1990 levels by 2050 requires a fundamental transformation of the energy sector. Especially in the electricity sector, Renewable Energy Sources (RES) play a major role to achieve these targets. The increasing share of intermittent electricity generation from RES leads to several challenges in the system. The availability of most technologies depends on the weather, e.g. wind or photovoltaic (PV) plants plants. Thus, electricity generation is not necessarily available when needed. In a system, with high RES capacity, times occur when electricity generation from these plants excess the demand as well as times, when they produce not enough electricity to fulfil demand requirements. The difference between electricity demand and RES generation is called residual load (Figure 1). The residual load duration curve helps to estimate the impact of renewables on the electricity system. The amount and number of hours with excess generation will increase with rising number of RES plants. On the other hand, electricity generation from wind and PV plants cannot be available during times with high demand. In this case, the peak of the residual load is not significantly lower than the one of the total load curve (Figure 1). As a result, high amount of back-up capacity would be needed to ensure security of supply. In addition, increasing the electricity generation from intermittent RES rises the gradient and volatility of the residual load. Flexibility options are required to balance these fluctuations. Miscellaneous technologies exist, which can provide flexibility. However, they show different technical and economic characteristics. Therefore, the objective of this paper is to deliver a structured overview on flexibility options for system integration of RES. For this purpose, flexibility option criteria are defined and serve as the basis for a comparative analysis which is presented in chapter 3 – 5 in this document.

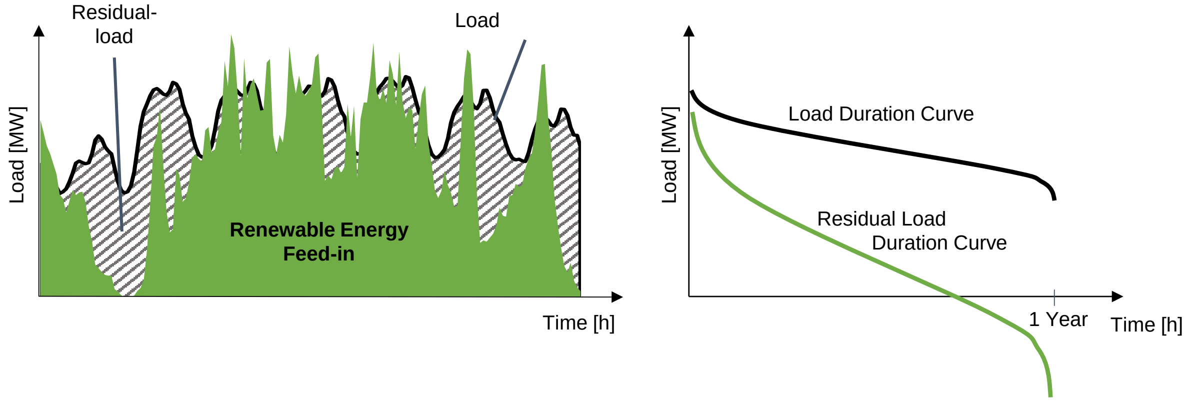

Figure 1: Definition of Residual Load and Residual Load Duration Curve (own illustration)

2 Overview Flexibility Options

The (future) need for flexibility is mainly caused by the residual load. Both, times with excess electricity generation from RES plants (negative residual load) as well as times with RES deficit (positive residual load) need to be balanced. Miscellaneous flexibility options exist, which can either provide flexibility in one of these two situations or in both (Figure 2). Therefore, the way of flexibility provision can be categorized in three different types:

- Downward-flexibility: Reducing or supplying the positive residual load (especially peak situations)
- Upward-flexibility: Reducing surplus RES feed-in from renewable energy sources by curtailing the excess amount or increasing the demand
- Shifting-flexibility: Shifting surplus feed-in of renewable energy sources to other regions or time steps with positive residual load as well as shifting positive load peaks to times with low or negative residual load.

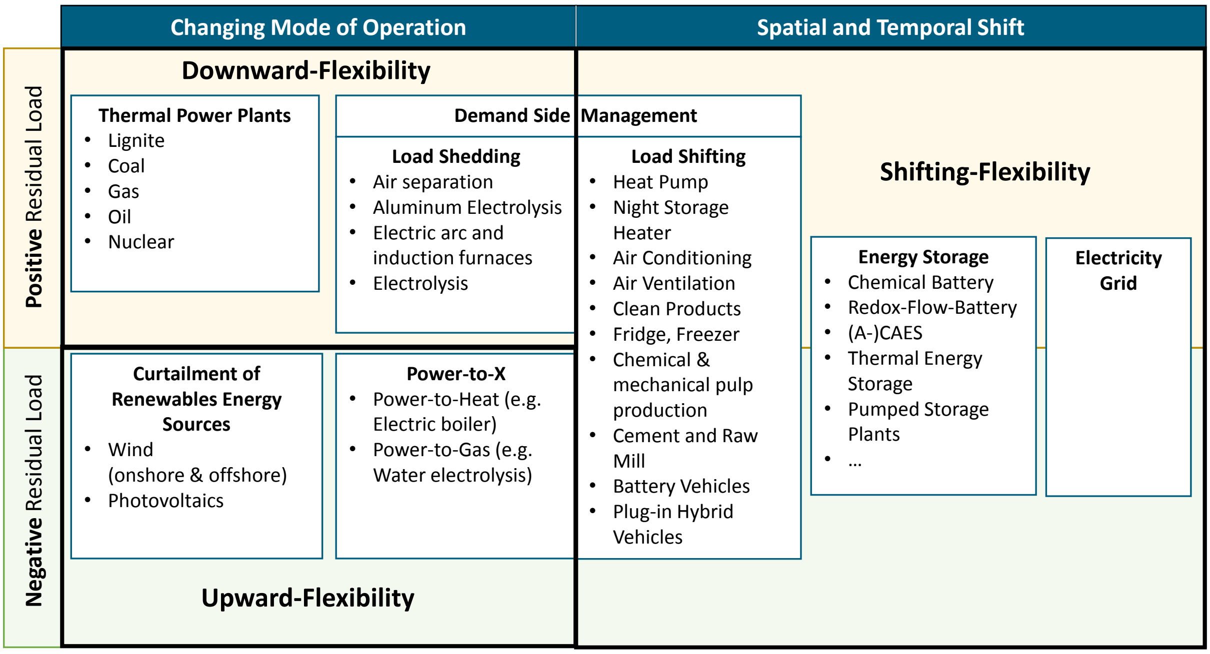

Figure 2: Overview flexibility options categorized in way of flexibility provision (own illustration)

The latter category involves technologies which can be used for spatial or temporal shifting. Electricity grids balance intermittent electricity generation in one region, by transferring excess electricity to another region. Energy storages as well as Demand Side Management (DSM) in terms of load shifting applications belong to the category temporal shifting. Energy storages can be charged with surplus electricity in times with negative residual load and discharged in time with positive residual load. The function of load shifting works the other way round. Respective applications reduce their demand in times when the residual load is (highly) positive and increase it again, when the residual load is low or negative.

In contrast to load shifting applications, load shedding applications decrease their demand without compensating the reduction at another time. They can be used for decreasing load peaks. Together with thermal power plants, they can provide downward-flexibility. The third category of DSM is Power-to-X. It is mainly used in times with negative residual load as it customs excess electricity for producing other energy carriers, e.g. hydrogen, methane or heat. Several studies showed, that integrating the available feed-in from RES plants completely is not cost efficient from a system perspective (e.g. Müller et al., 2013). Therefore, curtailment of RES represents a flexibility option as well. Together with Power-to-X it provides upward-flexibility.

There is a trade-off between the presented flexibility options. Some are complement and other compete with and among a category. Especially flexibility options belonging to the category “shifting-flexibility” fulfil the categories “downward-“ and “upward-flexibility” as well. To assess, which of these technologies can provide the flexibility needs in each of the three categories best, technical and economic characteristics need to be considered. For this purpose, the comparison is based on the following flexibility criteria:

- Activation time: How long does it take to provide flexibility (e.g. to start the operation of a plant or change its output)?
- Duration of flexibility provision: How long can the technology provide flexibility (e.g. the maximum number of hours to discharge a full storage completely)?
- Number of activations: How often can the flexibility option be dispatched (e.g. load shedding activities of industry processes are limited to minimize the impact on the production itself)
- Activation costs: Which cost occur, when the flexibility option is required and used. These are mainly variable costs.

This report focusses on the assessment of those technologies presented in Figure 2. The glossary at the end of this document provides a short definition of each technology. The comparative assessment with focus of each flexibility-category is presented in chapter 3 – 5. Detailed information about technical and economic characteristics of the flexibility options are presented in Görner & Sauer (2016) and Papaefthymiou et al. (2014) as well.

3 TECHNOLOGIES PROVIDING DOWNWARD-FLEXIBILITY

Relevant parameters for the comparison of technologies that provide downward-flexibility are activation time, the maximum duration of flexibility provision and the maximum number of activations per year. The key options that are able to provide downward-flexibility are conventional power plants (with or without CHP) as well as load shedding applications, mainly in the energy-intensive industry. Hereinafter, these options are compared regarding the derived parameters. Due to the similarity of parameters of CHP and thermal power plants, the parameters of CHP are not indicated in the following figures.

The activation time describes the time span until the power consumption or output of a technology can be varied. Figure 3 shows that load shedding applications can be activated within seconds up to few minutes and therefore are more flexible than most conventional power plants. Especially applications in the industry sectors aluminium electrolysis, electrical arc and induction furnaces as well as electrolysis have low load change times of few seconds until 15 minutes.

Peak power plants using natural gas can be activated faster than mid or baseload plants. Gas turbines are more flexible than cement and raw mills and can even compete with load shedding applications in some situations. New power plants are an option to increase the system flexibility. State-of-the-art coal and lignite power plants can halve the load change time and significantly accelerate the cold start compared to existing power plants. When operational, nuclear power plants are able to balance the generation to some extent, however when a cold start is needed they are very inflexible.

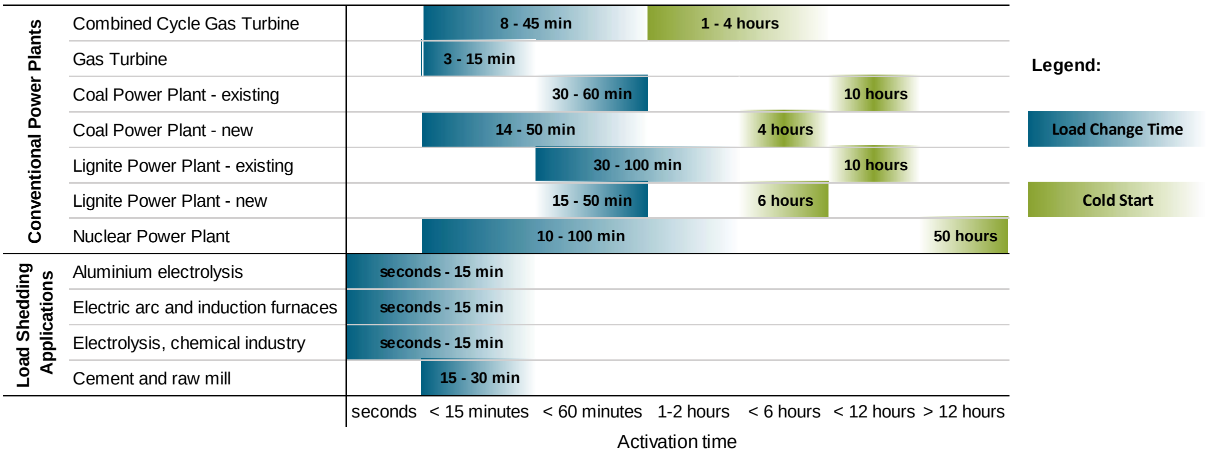

Figure 3: Activation time of load shedding applications in comparison to conventional power plants (Data source: Görner, Sauer 2016; Schröder et al. 2013)

Figure 4 depicts the maximum duration of downward-flexibility provision of the considered technologies. Conventional power plants theoretically have an almost unlimited maximum duration. As long as the adjusted operation mode with reduced electrical output is economically feasible, flexibility can be provided.

On the other hand, load shedding applications have a very limited time span of flexibility provision. Demand side measures are therefore disadvantaged compared to measures on the generation side. The highest timespan of flexibility provision can be reached with chemical and mechanical pulp production followed by the aluminium electrolysis. The remaining technologies are rather suitable for shorter periods, whereby maximum duration of flexibility provision is highly situational in the chemical industry and in cement and raw mills

To sum up, load change applications can flexibly balance load variances in the short-term due to their brief activation time. However, for longer periods of downward-flexibility provision - caused for example by lack of wind feed-in – demand side measures are not suitable and additional generation by conventional power plants is required.

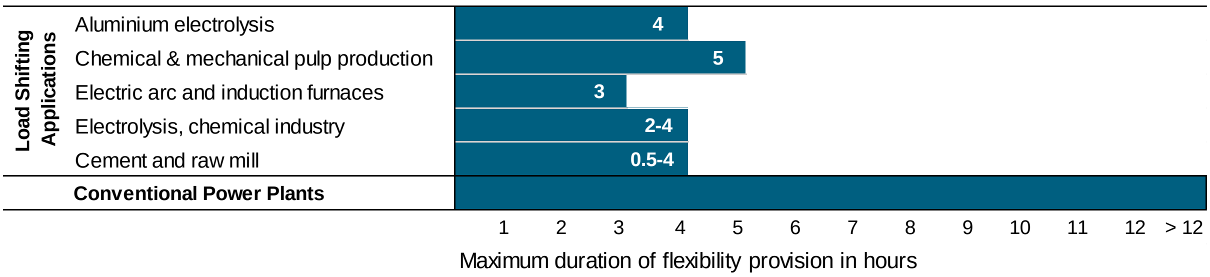

Figure 4: Maximum duration of flexibility provision of load shedding applications in comparison to conventional power plants
(Data source: Klobasa et al. 2013, own assumptions)

Furthermore, the maximum number of activations per year is crucial for assessing the suitability of different flexibility options, especially on the demand side. As Figure 5 shows, conventional power plants can be activated far more often than load shedding applications. Analogous to the maximum duration of flexibility provision, the limit of maximum activations is hereby given by economical restrictions. The utilization of load shedding applications is rather limited on average. However, cement and raw mills can be activated on a daily basis and electric arc furnaces can provide up to 200 usages.

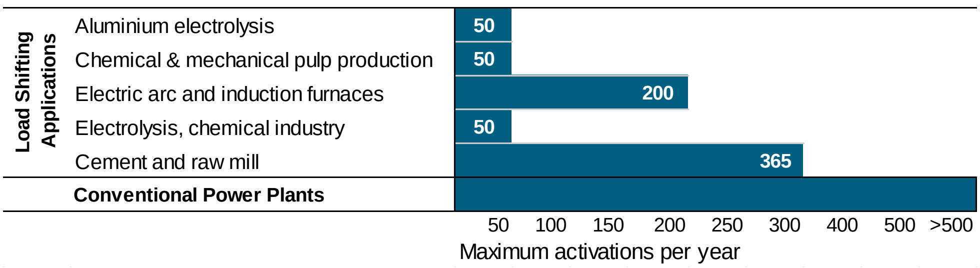

Figure 5: Maximum number of activations per year of load shedding applications in comparison to conventional power plants
(Data source: Klobasa et al. 2013, own assumptions)

Apart from technical characteristics, economical parameters have to be considered. For this purpose, activation costs are introduced. They represent the costs for activating and using the flexibility potential. For conventional power plants these are variable generation costs, which were calculated based on the data presented in

Table 1. Prices for fuel and CO_2-allowances are hereby given in bandwidths due to their uncertain development that is affected by a variety of external parameters. For load shedding applications activation costs are mainly opportunity costs, which represent the loss of production. Most of the time, decreasing the electricity production of an industry process goes in line with less production. Therefore, revenues for load shedding need to compensate (at least) the loss of production or the higher costs for larger stock-keeping.

Table 1: Assumptions for calculating activation costs for conventional power plants (Data source: Capros 2016, Schröder et al. 2013)

<table>
<tr><th rowspan="3"></th><th rowspan="2">Emission factor</th><th rowspan="2">Efficiency</th><th rowspan="2">Other variable costs</th><th colspan="2">Fuel price</th><th colspan="2">Price for CO_2-allowances</th></tr>
<tr><th>Min</th><th>Max</th><th>Min</th><th>Max</th></tr>
<tr><th>t/MWh_{th}</th><th>%</th><th>$€/MWh_{el}$</th><th>$€/MWh_{th}$</th><th>$€/MWh_{th}$</th><th>$€/t_{CO2}$</th><th>$€/t_{CO2}$</th></tr>
<tr><td>Combined Cycle Gas Turbine</td><td>0.202</td><td>60</td><td>2</td><td rowspan="2">27.6</td><td rowspan="2">59.5</td><td rowspan="7">10</td><td rowspan="7">90</td></tr>
<tr><td>Gas Turbine</td><td>0.202</td><td>39</td><td>1.2</td></tr>
<tr><td>Coal Power Plant - existing</td><td>0.354</td><td>49</td><td>6</td><td rowspan="2">12.4</td><td rowspan="2">21.8</td></tr>
<tr><td>Coal Power Plant - new</td><td>0.354</td><td>52</td><td>6</td></tr>
<tr><td>Lignite Power Plant - existing</td><td>0.364</td><td>43</td><td>6.5</td><td rowspan="2">1.5</td><td rowspan="2">1.5</td></tr>
<tr><td>Lignite Power Plant - new</td><td>0.364</td><td>47</td><td>6.5</td></tr>
<tr><td>Nuclear Power Plant</td><td>0</td><td>34</td><td>5</td><td>2.4</td><td>9</td></tr>
</table>

In order to economically compare load shedding applications and conventional power plants, activation costs are calculated and depicted in Figure 6. It appears that conventional power plants generally have lower activation costs than load shedding applications. Cost bandwidths likewise tend to be smaller in conventional power plants. However, demand side measures can be competitive depending on the specific framework conditions, like the price of the industry's end product or fuel and CO_2-costs on the generation side.

Baseload power plants generally have lower activation costs than peak plants due to cheaper fuels. Increasing prices for CO_2-allowances however can change this order favouring gas technologies. Differences in activation costs between existing and new power plants because of higher efficiency standards are relatively small. Furthermore, activating CHP technologies tends to be slightly more expensive than doing so for non-CHP plants.

On the demand side cement and raw mills stand out thanks to the lowest and least volatile activation costs. The usage of aluminium electrolysis and electrolysis in the chemical industry may be economically reasonable, but activation costs vary strongly. Chemical and mechanical pulp production are the least favourable application out of all (downward-) flexibility options

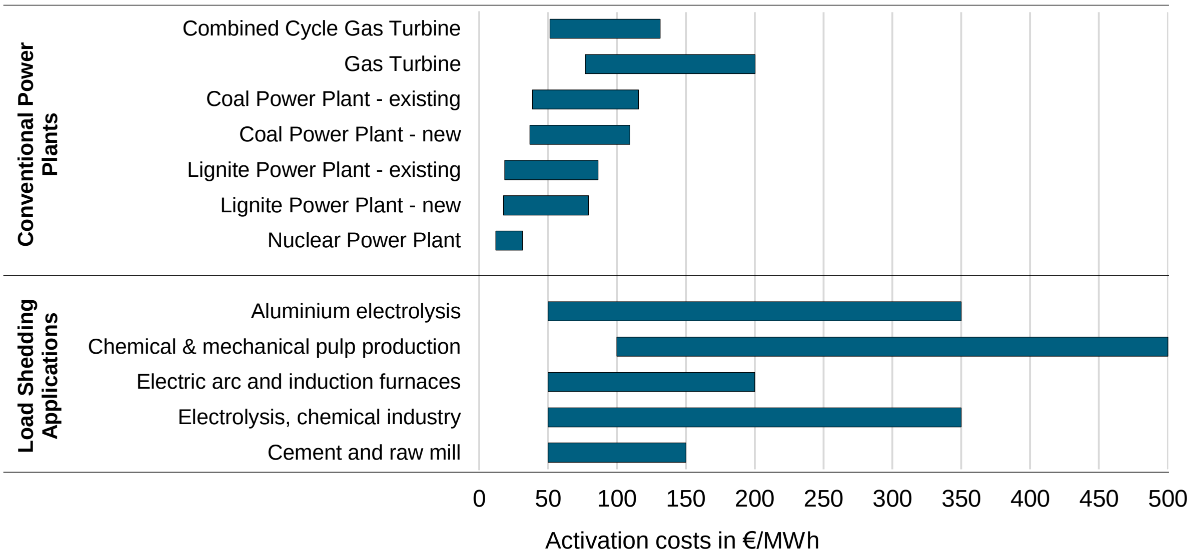

Figure 6: Activation costs of load shedding applications in comparison to conventional power plants (Data source: own calculations, Klobasa et al. 2013)

From a short term perspective and with regard to existing plants, electricity generation of thermal power plants is more cost efficient than load shedding comparing activation costs. However, if investments in new generation capacity is needed, this picture can change. A lot of industry plants are already equipped with energy management systems. Thus, the costs for exploiting the respective potential are quite low. In comparison, investment costs for new power plants are higher. Beside, load peaks only occur for a few hours a year. Therefore, it could be more cost efficient to compensate rare load peaks with load shedding instead of building a new plant. However, they can only provide their flexibility for a limited number of hours. Thus, for longer periods of positive residual load, (additional) power plants are needed.

4 Technologies providing Shifting-Flexibility

Various technologies are considered when analysing flexibility options for spatial or temporal shifting: technologies are related to different categories, such as energy storage, energy demand appliances with the potential for shifting the use of related equipment (DSM) or electricity grids. Therefore, the comparison is made among technologies with different fields of application, e.g. demand management of electric products (such as washing machines, dryers, freezers, etc.), options related to the electrification of other sectors (such as electric vehicles, heat pumps, water heating, etc.), or energy storage technologies (such as pumped storage, (A-)CAES and batteries).

For demand flexibility it is of importance within which timeframe the needed capacity is available for either decreasing or increasing load. On the demand side, most of the equipment can provide positive or negative capacity within seconds (see Figure 7). By simply switching the device on or off, electricity demand can be increased or decreased, providing the needed flexibility. This especially applies for all types of heat pumps, ventilation and cooling devices, white goods as well as special forms of electric of heat storage devices. More large scale appliances however need several minutes to provide full capacity.

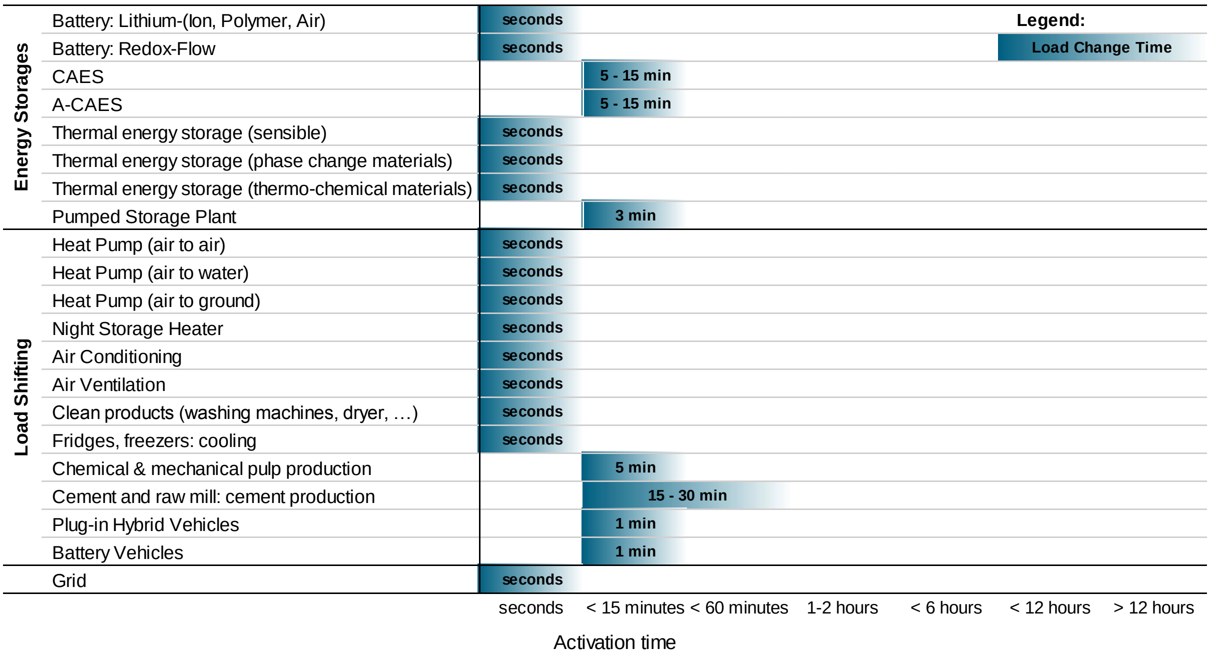

Figure 7: Activation time of energy storages and load shifting applications (Source: own assumptions)

Maximum duration of flexibility provision depends mainly on the storage size attached to the demand device and varies between several hours to unlimited periods (see Figure 8).

In case of heat pumps, warm water tanks are usually of a size of a few hundred litres and therefore the duration for increasing electricity demand lasts up to a few hours, depending on the temperature level of the water in the storage before activating the heat pump again. On the other hand, reducing electricity demand for heat pumps can last for more hours, depending on the heat storage within the building and the outside temperature.

Depending on the purposes, thermal storage technologies are used for short-term (buffer or daily) or long-term (seasonal storage). In general, the charging process requires shorter time than discharging process. However, the exact duration depends on the design. The typical duration of charge/discharging time for short-term is 2 - 14 hours. For long-term storage the charging/discharging time depends on the size of the storage media. In a water tank example with 20000 m^3 capacity, it can be discharged continuously up to 60 hours during summer to cover hot water demand.

For other appliances such as electric vehicles, the duration of flexibility mainly depends on the remaining storage capacity (if the batteries are not empty), the charging power (i.e. the type of the charging infrastructure characteristics, slow, medium or fast) and the time available until the storage device needs to be fully charged again. Since cars are often used for commuting, the maximum duration of flexibility provision depends on the use of the electric vehicle and can range up to several hours. In principle, taking into account only the use of the vehicle, the duration of flexibility provision could last up to 20 hours (as a large share of vehicles are not used for most of the day). Nevertheless not all users have the same driving profile and some cars are used much more frequently over the day. Furthermore also the other technical elements mentioned above should be considered at the same time. In fact, it should be reminded that the duration for full charging / discharging the battery of a single vehicle with normal charging power could last about 8 hours. In summary, the duration of flexibility for electric vehicles is strictly dependent on user preference besides the technical constraints.

For other devices there is no such differentiation, once the storage device is empty, the device needs to go online immediately to avoid either loss of comfort (e.g. ventilation needs to go back online once the demand has been shifted and air quality levels reach a defined low) or other predefined costumer preferences and therefore the maximum duration time is limited.

In summary, the selected technologies show a wide range of variability in terms of duration of the flexibility provision: depending on the needs for load shifting different technologies should be selected. In principle, the duration of flexibility provision of load shedding application is lower than for energy storage. Thus, they can mainly be used for balancing short term fluctuations while energy storage can also compensate longer periods with RES deficit.

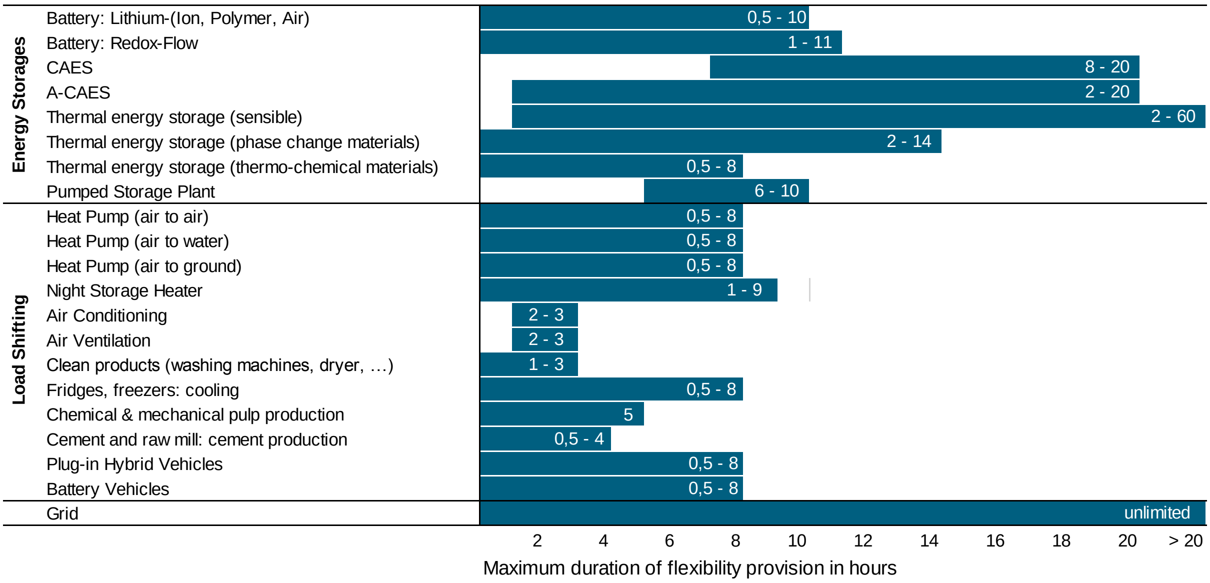

Figure 8: Maximum duration of flexibility provision of energy storages and load shifting applications (Source: own assumptions, Dinçer & Rosen 2011)

Another relevant factor regarding flexibility provision is the maximum number of activations per year (see Figure 9 for detailed overview).

Depending on the seasonality, (heat pumps in cold times, air conditioning in warm periods) or other regulations (pumped storage limited by specific parameters such as minimum and maximum water level at certain times, etc.), the number of activations varies between a few hundred activations to more than 1000 activations per year. The higher the number of activations, the higher the flexibility provision, especially to balance periods with highly fluctuating generation (e.g. solar generation in cloudy weather).

For thermal energy storage, the number of activation of short-term storage could be one to several times per day (300 - 3000 times per year), while the storage cycle for long-term storage is one time per year.

With reference to plug-in hybrid and battery electric vehicles, it is assumed that the flexibility provision could be activated a few times per day (e.g. 2 or 3 times per day, 730 - 3160 per year). In fact, the assumption takes into account not only the technical feasibility but also the so-called 'range anxiety' of the vehicles owners, referring to the concern and fear of a discharged battery with a limited range vehicle.

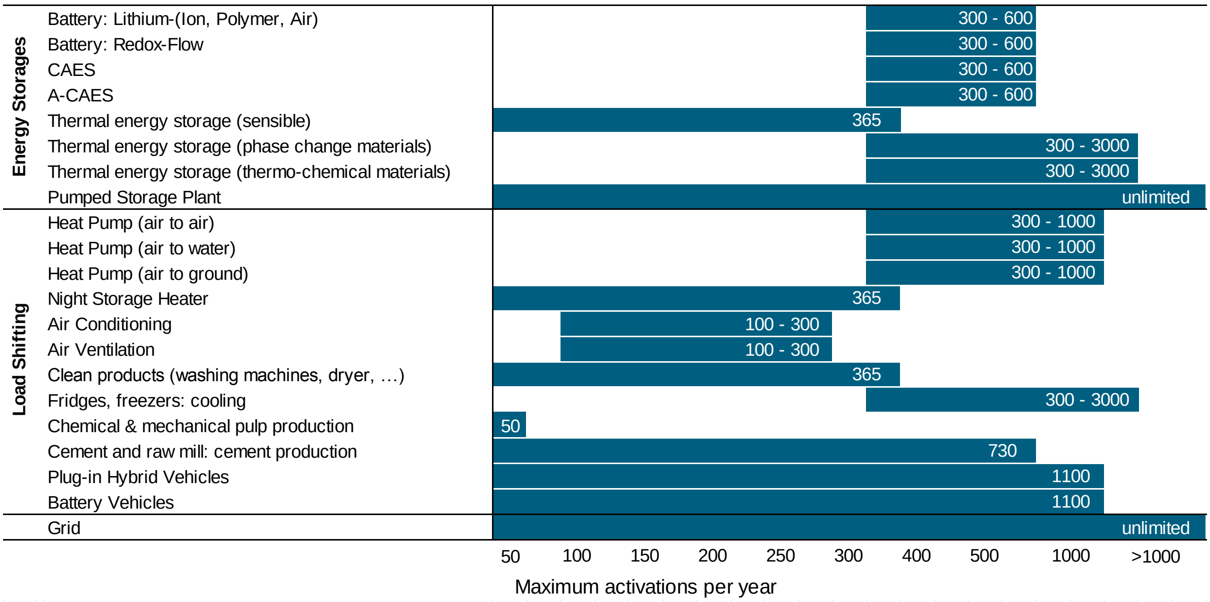

Figure 9: Maximum number of activations per year of energy storages and load shifting applications (Source: own assumptions, IEA-ETSAP & IRENA (2013)

Looking at the list of technologies from an economic perspective, the flexibility options have been compared in terms of activation costs, i.e. the costs for activating and using the flexibility potential.

The activation cost varies between almost zero additional costs (e.g. modern heat pumps which are already equipped with control devices (Bossmann et al., 2015)) up to several hundreds of Euros per MWh (see Figure 10).

The activation costs of thermal storage technologies are calculated based on the annual operation hours and annual specific O&M costs. The annual operation hours depend on the function of the thermal storage according to Dincer & Rosen (2010) and the annual specific O&M costs are provided by IEA-ETSAP & IRENA (2013).

For battery and plug-in hybrid electric vehicles the activation costs considered for the analysis refer to the operating cost related to electricity consumption for travelling, counterbalanced by the revenues for feeding back the power in case of vehicle-to-grid activation. Table 2 summarizes the hypothesis used for the estimation, under different assumption in terms of V2G operation and the related electricity price for energy provision. The resulting range of activation costs from the user perspective is between 100 to 300 Euro/MWh (with an average electricity consumption of about 2 to 4 MWh/year).

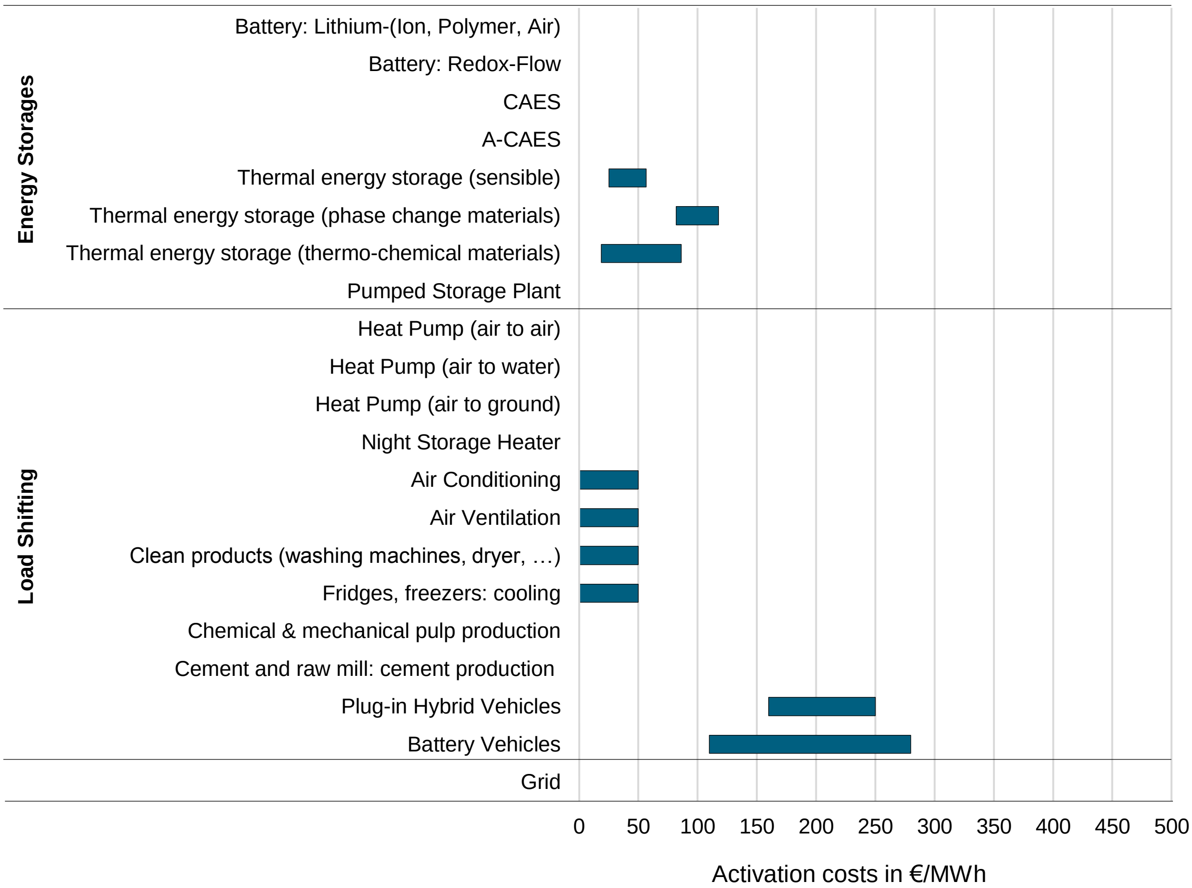

Figure 10: Activation costs of energy storages and load shifting applications (Source: own calculations, Bossmann et al. 2015, Dincer & Rosen 2010, IEA-ETSAP & IRENA 2013)

Table 2: Assumptions for calculating activation costs for battery and plug-in hybrid electric vehicles (Source: COFYS 2014, CE Delft 2011, own assumptions)

	battery electric vehicle	plug-in hybrid vehicle
average yearly distance travelled (km)	15,000	15,000
average consumption (kWh/km)	0.15	0.13
average V2G energy provision per activation (kWh)	6.5	2.3
number of activation per day	1 or 2	1 or 2
Percentage of V2G activation in a year	30% to 100%	30% to 100%
Electricity price for consumption (euro/kWh)	0.22	0.22
Electricity price for V2G energy provision (Euro/kWh)	0.15 to 0.22	0.15 to 0.22

5 TECHNOLOGIES PROVIDING UPWARD-FLEXIBILITY

Technologies that provide upward-flexibility are needed if electricity generation exceeds demand during times of high feed-in by variable RES. In general, two concepts can be distinguished: either RES feed-in is turned down or electricity consumption is increased. The corresponding technologies are wind power plants (on- and offshore) and photovoltaic plants on the supply side and Power-to-Heat as well as Power-to-Gas concepts on the demand side. In this section, electric boilers represent Power-to-Heat applications and water electrolysis is considered for Power-to-Gas concepts.

One important criteria for flexibility options is the activation time. The feed-in of wind and photovoltaic plants can be regulated downwards or even curtailed within seconds or minutes. The same reaction time applies to Power-to-Heat and Power-to-Gas: electric boilers and water electrolysis can be turned on within seconds or minutes, depending if it is a cold start or the plant was operated in stand-by before.

If a wind or photovoltaic plant is used for flexibility provision, it can be turned off or curtailed for an indefinite time period. During that time, no or only a part of the potential electricity generation is fed into the grid. If the situation changes and electricity generation is needed, the feed-in of RES is permitted and can be realized within seconds or minutes.

On the demand side, the duration of flexibility provision (in this case: demand increase) depends on the need for heat or gas respectively. For electric boilers, it can be assumed that they are switched on for 2 to 12 hours approximately. However, if that situation occurs in summer, it has to be ensured that there is a need for heat because otherwise this activation would be counterproductive. For Power-to-Gas, the duration of flexibility provision depends on the need for hydrogen. In general, this process can run for an indefinite period of time, depending on the size of the hydrogen storage and the subsequent processing steps. But as most following processes like methanation or methanol synthesis prefer a stable hydrogen supply, longer time periods of flexibility provision would be better.

The feed-in of wind or photovoltaic plants can be turned down as often as necessary during one day, so the number of activations per day is unlimited. The same applies to Power-to-Gas: if the water electrolysis is operated in stand-by operation, it can be regulated down- and upwards very often. In the case of electric boilers, it is assumed that the operation is limited to 90 interventions per year.

The standard case for RES curtailment describes the situation that feed-in of RES is limited if it exceeds demand and thus, residual load is increased. However, from a technical point of view, it is also possible that RES feed-in is limited in general and increased if electricity supply is needed. This could make sense if very high shares of RES are reached within energy systems and some of the RES plants are used for peak shaving. However, this would result in high costs as these plants would show low full load hours.

The activation of Power-to-Heat and Power-to-Gas leads to an increase of the residual load as well. But also in this case, the opposite would be possible: a stable operation (which means constant electricity consumption) and a selective lowering of electricity consumption if electricity production is scarce.

The technical constraints of RES curtailment and demand increase of Power-to-Heat or Power-to-Gas show that all applications allow a very flexible operation. Thus, it is difficult to differentiate them by means of technical characteristics. However, the economic figures make clear that the costs linked to the utilisation of these flexibility options differ. So, activation and initialisation costs are analyzed in the following.

Activation costs contain the variable costs that occur if a flexibility option is required. In case of RES curtailment, they amount to the levelized cost of electricity as the operators of RES plants have to waive the revenues that would be possible if they would sell the electricity. For Power-to-Gas and Power-to-Heat, the activation costs are negative: these operators are willing to pay for electricity if they can produce hydrogen or heat for production costs lower than the common market price. So, activation costs indicate that demand increase means no additional costs if RES oversupply occurs. Figure 11 illustrates the minimum and maximum ranges of the considered flexibility options.

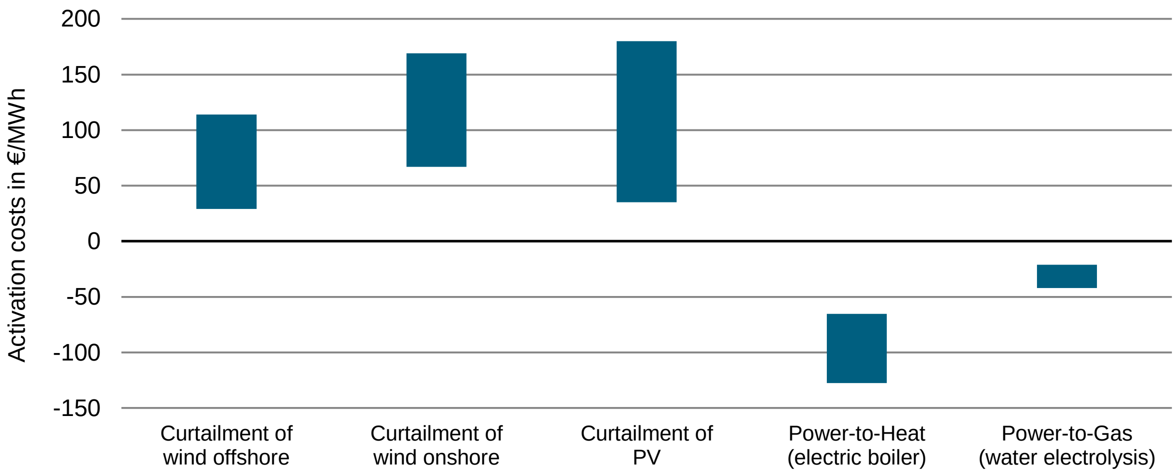

Figure 11: Activation costs of upward-flexibility options (source: VGB Powertech 2015, BDEW 2009, Zech et al. 2010, Müller-Syring et al. 2013, Körner 2015)

However, not only activation costs, but also initialisation costs have to be considered. They illustrate that investments are needed in order to build and maintain flexibility options. In case of RES curtailment, these costs include only the equipment and service for a control element. But in case of the demand technologies, the whole investment and operation and maintenance costs for an electric boiler or the water electrolysis have to be considered. By consequence, the initialization costs of Power-to-Gas and Power-to-Head exceed those of RES curtailment by far as it is shown in Figure 12.

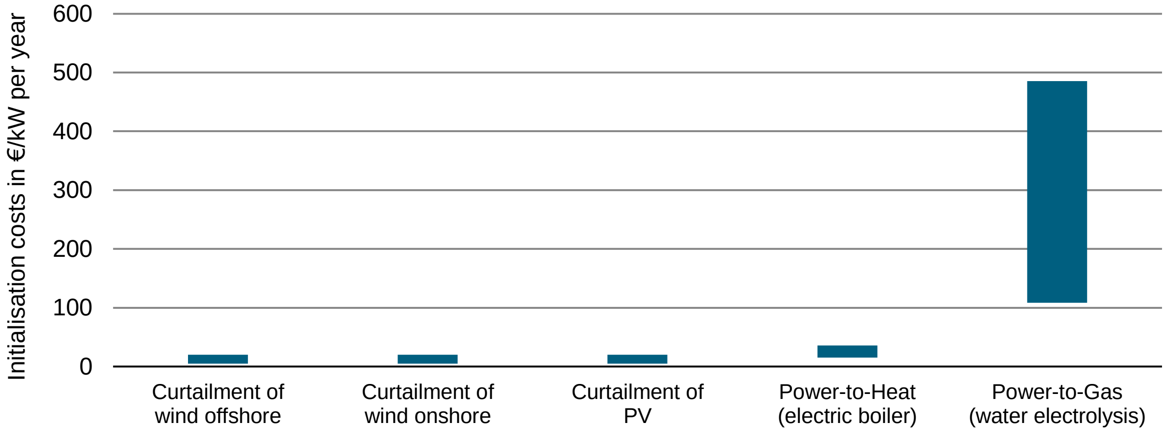

Figure 12: Initialisation costs of upward-flexibility options (source: VGB Powertech 2015, Groscurth und Bode 2013, FfE 2014, Körner 2015)

Summarised, the upward-flexibility options show similar technical characteristics with regard to a flexible operation but differ in terms of costs. The built up of Power-to-Heat or Power-to-Gas technologies depends in particular on the frequency and temporal distribution of the situations that require upward-flexibility. If RES feed-in exceeds demand only for a few hours during the year, RES curtailment is more suitable from a cost perspective. However if RES surplus occurs on some thousand hours a year, the built up of Power-to-Heat or Power-to-Gas should be considered.

6 SUMMARY

In future markets with increasing shares of RES, additional flexibility is needed to maintain system reliability. Therefore, flexibility options are required to balance load fluctuations.

This document provides a structured overview on flexibility options for system integration of RES, compared under different criteria. The way of flexibility provision has been categorized in three different types: downward-flexibility (reducing or supplying the positive residual load), upward-flexibility (reducing excess feed-in of renewable energy sources) and shifting-flexibility (spatial or temporal shifting). Of course, there is a trade-off between the technologies taken into account in the analysis: some are complement and others compete with and among a category.

Downward-flexibility can be offered by conventional power plants and load shedding applications. Load shedding technologies show a considerable low activation time, but are limited with regard to the maximum duration of flexibility provision. For conventional power plants it is converse: they need minutes to hours for activation but have an almost unlimited duration time. The same applies to the number of activations per day that show stricter limits for load shedding. The economical comparison of activation costs clarifies that conventional power plants have in general lower costs, but uncertainty is very high for these parameters and the picture could change if framework conditions like prices for fuel or CO_2 allowances rise. As a result, the flexibility potential of conventional power plants for downward-flexibility seems attractive as it shows better values for most parameters. However, in some situations, a very immediate flexibility need will occur where load shedding has the advantage of a small activation time.

Technologies providing **shifting-flexibility** comprise various applications like storage, DSM technologies and electricity grids. The comparison of activation time shows that all applications need only seconds to minutes for delivering flexibility. Especially grid activation, heat pumps, ventilation and cooling devices, white goods, batteries and thermal energy storage have a very low reaction time. With regard to the maximum duration of flexibility provision, the shifting-flexibility technologies show a wide range. The grid, large-scale electricity storage and some thermal storage have very high duration times. However, the duration of flexibility provision of storage depends strongly on the storage capacities. Furthermore, the seasonality influences the flexibility parameters, e.g. activation of heat technologies is only possible in cold seasons or large heat storage capacities are needed additionally. The number of activations varies between a few hundred to more than 1000 activations per year for all considered shifting-flexibility technologies. Very high numbers are possible for thermal energy storage, heat pumps, fridges, electric vehicles and the grid. From an economic perspective, electricity storage technologies, heat pumps, cooling technologies and clean products have very low activation costs compared to electric vehicles or thermal storage. It can be concluded that among the shifting-flexibility technologies, there is not one technology that shows best results for all parameters. But it becomes clear that the electricity grid shows some advantages for flexibility provision and that DSM applications can compete with storage in many parameters.

Upward-flexibility can be offered by curtailment of wind or photovoltaic power plants and the use of Power-to-Heat or Power-to-Gas concepts. All technologies show low activation times of seconds or minutes and most of them have an almost unlimited duration of flexibility provision. However, the use of Power-to-Heat depends on the heat demand and if this demand exists, electric boilers are switched on approximately for some hours, but not continuously for days or weeks. The number of activations is unlimited for the renewable power plants and also for Power-to-Gas, because the electrolyzer can be operated in a very flexible way. The operation of electric boilers is limited to less than hundred interventions per year but Power-to-Heat has the lowest activation costs among the considered technologies because operators would be willing to pay for the electricity and thus, activation costs turn negative. The same applies to Power-to-Gas. However, initialisation costs are high for Power-to-Gas because investment is high. Power-to-Heat and wind or photovoltaic plants have lower initialisation costs. As a result it can be stated that upward-flexibility options show similar technical parameters but with regard of economic values, Power-to-Heat and curtailment of RES is more attractive than the use of Power-to-Gas.

As an **overall result**, this analysis clarifies that many different flexible technologies will be available in the future. Some technologies are suited for flexibility provision from a technical perspective but their use is limited because of restrictions e.g. when DSM applications are used for industrial production. Other options like energy storage can be operated in a very flexible way, but investment is high, so they need high full load hours for a profitable operation. Thus, it is not possible to choose one or a few flexibility options to cover the future need within this analysis. Very different challenging situations will occur that must be met by a mix of technologies. But if some applications compete for the same type of flexibility provision, cost-effectiveness among them will decide which one will prevail. This competition of flexibility options will be examined in the model based analysis of REFLEX.

7 Glossary

7.1 Supply Side

Thermal power plants

Thermal power plants mainly use fossil fuels like coal, lignite or natural gas in order to generate electricity. The main technologies are open cycle gas turbines, combined cycle gas turbines, coal- or lignite-fired steam turbines as well as nuclear power plants.

- **Open cycle gas turbines (OCGT)** are combustion turbines fired by natural gas. High-pressure gas is expanded to directly turn the blades of a turbine.
- **Combined cycle gas turbines (CCGT)** combine a gas-fired turbine with a steam turbine. The design uses exhaust heat from the gas turbine in order to create steam, which in turn drives the steam turbine. The combination of processes significantly increases the efficiency.
- **Steam turbines** operate similar to gas turbines, except that steam is used instead of compressed air. The dynamic pressure generated by expanding steam is used to power the turbine. Main fuels are coal and lignite.
- **Nuclear power plants** are also characterized as thermal power plants, although not fired by fossil fuels. They use heat generated by nuclear fusion to drive steam turbines likewise.

To date, thermal power plants are the main providers of system flexibility by balancing residual load. However, flexibility is limited due to the inert operation mode. Key constraints are defined by technical restrictions like minimum load requirements, ramping capabilities as well as must-run capacities. These restrictions vary between different technologies. New state-of-the-art plants can increase the flexibility of thermal generation due to recent technology developments.

Renewable Energy Sources

Renewable Energy Sources (RES) generate energy from natural resources such as sunlight, wind, biomass, hydro, tides and geothermal heat. While volatile RES, namely **wind (onshore & offshore)** and **solar power**, are the main drivers of the increased flexibility demand in electricity systems, they can also provide flexibility through active power control. This term describes the curtailment of power production in order to balance the system generation and therefore the provision of upward-flexibility in times of excess feed-in of RES. Downward-flexibility can be provided by operating plants at lowered generation levels so that electrical output can be increased when needed. The technical capability for providing fast response to regulation signals is given for wind turbines as well as PV modules.

Beside these volatile RES, technologies exist, which can ramp up and down electricity production reacting flexible to changes in residual demand. These are hydro and biomass power plants. The electricity production via **biogenic fuels** (biogas, biomass) or **hydro** (run-of-river, reservoir) is also considered renewable. Generation principally can be ramped up and down reacting to changes in residual demand. However, most biogenic fuel facilities are currently operated according to heat production needs and thus increase the flexibility demand by providing must-run capacities. Flexible electricity-led operation can be enabled by installing heat storages. The operation of hydro storage plants is mainly driven by the availability of water, which strongly varies during the year. However, reservoir power plants can operate quite flexible due to their natural storage.

7.2 Energy Storages

Battery: Lithium-(Ion, Polymer, Air) and Redox-Flow

Batteries respectively accumulators are electrochemical energy storages that make use of reversible chemical reactions. When charging, a chemical redox reaction is initiated by applying a voltage source. During the discharge process the stored energy is converted back into electrical energy. Batteries therefore can provide downward- as well as upward-flexibility. A distinction is made between internal and external storages. The location for storage and conversion of energy is the same in internal technologies, but different in external technologies. In the latter case, storable capacity and power are thus independent and can be dimensioned separately. Key technologies for internal storages are Lithium-Ion-Batteries, for external storages Redox-Flow-Batteries.

- **Lithium-Ion-Batteries** are conventional batteries that are composed with cells which contain two electrodes. They cover all accumulator technologies based on lithium compounds.
- **Redox-Flow-Batteries** use electrolyte liquids in tanks, which can be stacked. The most commonly used type is the vanadium redox battery.

Battery systems are defined and assessed using various parameters such as energy density, lifespan, self-discharge rate, efficiency and costs.

CAES and A-CAES

Another storage option that is scarcely used until now is the **Compressed Air Energy Storage (CAES)**. Hereby, energy is stored mechanically through electric motors that compress air into enclosed volumes, mainly underground caverns. During the discharge, compressed air is directed to a turbine / generator unit where it is expanded. The combustion turbine thereby consumes fossil or biogenic fuel.

Advanced Adiabatic CAES (AACAES) capture the heat that is produced as a by-product during compression. In discharge mode it is used to heat the air as it passes to the combustion turbine inlet. This second generation technology can increase operation efficiency by 20 % compared to standard CAES and ensures a carbon free operation. However, projects of considerable size are not yet carried out. Key barriers are high capital costs and the specific geological site requirements.

Thermal Energy Storage

Thermal energy storage technologies store energy in three main types: sensible heat, latent heat and chemical energy. Currently the sensible thermal energy storage systems are commercially available, while PCM and TCS are still under research and development.

- **Sensible thermal energy storage** is the most common thermal storage type. It relies on the specific heat and thermal capacity of the storage media, which can be liquid or solid.

- **Phase change materials (PCM)** can store energy by the latent heat of the storage media which enables higher capacity and potential of targeting constant discharging temperature.
- **Thermo-chemical energy storage (TCS)** achieves high energy density by chemical reactions such as adsorption. It can be used to store and release heat and cold as well as to control humidity.

Sensible thermal storage is the most developed technology which is used in both short-term and long-term storage. Phase changing material is mostly used in daily storage by storing the solar energy during the day and releasing energy at night. Thermo-chemical material is not yet commercialized but most likely will be used as buffer storage.

Thermal energy storages also provide flexibility by enabling combined heat and power plants (CHP) to work in electricity-led operation by decoupling the electricity generation from the heat provision. Also while using excess electricity in other energy sectors (see Power-to-Heat technologies) thermal energy storages can increase the flexibility potential.

Pumped Storage Plant

Pumped Storage Plants (PSP) are a mechanical storage technology consisting of two water reservoirs at different heights, interconnected by pressure pipelines. PSP store energy by electrically pumping up water from a lower to an upper reservoir in times of power surpluses. The quantity of stored energy depends on the difference in height and the overall water mass. When electricity demand is high, power is produced by letting the water flow back through turbines, similar to traditional reservoir plants. PSP are currently the only market proven storage technology and provide high efficiencies of 70 to 85 %. However, costs are highly situational and siting requirements very specific.

7.3 Demand Side

Heat pumps

Heat pumps transfer heat from a medium with a low temperature to a medium with higher temperature, increasing the temperature level of the warm medium and reducing the temperature level of the cold medium. Both media must be separated by a boundary layer to prevent short circuits. To maintain the heat transfer, the system needs the input of electricity. Heat pumps are often equipped with storage tanks to have the heat easily available when needed. Due its storage capability, heat pumps offer a flexibility capacity in both directions. In case of excess electricity, heat pumps can be switched on very short notice and heat up the storage medium. In case of electricity scarcity the heating process can be postponed, running equipment can be temporarily shut down or its electricity consumption can be reduced.

For space heating and warm water, various sets of heat pumps are available, which are often classified by the medium of the heat source and the medium of the heat sink. In this project three different heat pump systems are classified:

Heat Pump (air to air/water): heat is extracted from the air outside of a building and used for either space heating by air ventilation systems (air to air) or by warm water cycles like floor heating (air to water). In air to water systems, the warm water can also be used for other domestic warm water uses.

Heat Pump (water to air/water): heat is extracted from usually shallow aquifers which are situated below or close to the building. The heat density in water as cold medium is much higher as in air and therefore, these heat pump systems are usually more efficient. The heat is transferred to either air or water, the heating medium in the building.

Heat Pump (water to air/water): heat is extracted from usually shallow aquifers which are situated below or close to the building. The heat density in water as cold medium is much higher as in air and therefore the heat pump system is usually more efficient in such case. The heat is transferred to either air or water as heating media in the building.

Heat Pump (ground to air/water) heat is extracted from usually deep aquifers or rock layers which are situated below or close to the building. The heat density in the deep layers is much higher as in air and therefore the heat pump system is usually more efficient for ground to air. The heat is transferred to either air or water as heating media in the building.

Night Storage Heater

Heat is generated by electric resistance and stored in a porous stone like clay within an insulated radiator. By heat radiation and convection the thermal energy is distributed for several hours within a room. Mostly decentralized radiator installations are used, but more centralized systems with a water based heat distribution are also available. The system is less and less in use due to technical (low efficiency) and political reasons.

Similar to heat pumps, the electricity demand from night storage heaters can either be postponed, increased or decreased depending on the electricity supply.

Air Conditioning:

Air conditioning is used to control air quality parameters such as heat and humidity. By extracting heat from air within a room/building, specified comfort levels are targeted and achieved. The demand for air conditioning is steadily growing in the recent years especially in the services sector.

Depending on the defined quality and comfort thresholds air conditioning is offering a DSM potential for either increasing or decreasing electricity demand for short periods.

Air ventilation:

Air ventilation is often used in large office and school buildings and in residential buildings with high energy efficiency standards (due to insulation and limited to no uncontrolled air exchange). Ventilation systems bring in fresh air (sometimes heated) and can additionally be equipped with humidifiers. Within the ventilated rooms the air quality is generally regulated by CO_2-concentrations meters influencing the use of ventilation systems.

Depending on some air quality thresholds and the installed controls, ventilation systems can offer a flexibility potential by either postponing the introduction of fresh air into a building until a certain quality reduction is reached and to a limited extend by bringing in more air then currently needed. However, since the air cannot be stored for long, and the CO_2-level cannot be reduced below natural levels, this DSM direction is limited.

Clean products:

All electric appliances within households used for either cleaning or drying are classified as clean products such as washing machines, dish washers, tumblers and driers. Depending on the definition, fridges or stoves can also be included in this group which is then classified as white goods. While some of the named products have favourable characteristics for demand side measures such as fridges (which can be used in two directions since their use is independent of a user), the other appliances have limited flexibility potential. The clean products can be used for increasing the electricity demand if needed, in case the user sets up the equipment accordingly (usually started in the morning, the process has to be finished by a specified time). However, these appliances cannot be interrupted once started since the output of the process cannot be guaranteed (e.g. loss of detergent once the washing machine is stopped and drained).

Fridges, freezers: cooling

Refrigerators and freezers, used for food cooling, can be found in nearly every European household. The main component of refrigerators and freezers is a compressor cooling machine. In the cooling compartment of refrigerators, temperatures vary between +2°C and +7°C, while in freezers they range from -12°C to -20°C (Stadler, 2005). Both types of appliance feature rated power of 50 to 300 W and a load factor of about 33% with continuous operation times of several minutes up to half an hour. Cold storage warehouses in the tertiary sector (mainly in food wholesale and retail, and in restaurants (VDE, 2012b) usually function according to the same principle as residential refrigerators or freezers, but with much bigger cooling compartments and at considerably higher rated power. According to Klobasa (2007) the total rated power can be shifted up to three hours given the higher storage capacity of such large-scale applications. (Boßmann, 2015)

Air separation: membrane

Air separation to gain nitrogen, oxygen and argon requires electricity intensive compression of air. According to Klobasa (2007) facilities can be operated at 70% part load whereas frequent ramping up and down of the process should be avoided (Boßmann, 2015).

Aluminium electrolysis

Primary aluminium is produced in a two-step procedure: bauxite is converted in a refinery via the Bayer process into aluminium oxide (alumina). This is subsequently reduced into aluminium metal via an energy intensive electrolysis process operating at 950°C (Hall-Héroult process), requiring 13-15 MWh per ton of Aluminium (EAA, 2008; VDE, 2012a). The electrolysis cells feature a 64% annual utilisation rate. They are available for load increase or decrease to part-load mode (about once per day) during several hours and for full load reduction of up to 4 hours. The time constraint is mainly related to the temperature of the electrolysis cell which must not drop below 930°C in order to avoid the destruction of the electrolysis plant (VDE, 2012a). According to Klobasa (2007) load reduction is allowed down to a level of 75% of the nominal load. (Boßmann, 2015)

Chemical & mechanical pulp production

Paper production consists of three main steps, each of them being very energy intensive and at the same time suitable for load shifting but to a varying extent: provision of raw material (pulp), conversion into paper, and refinement of the product. Pulp production is a continuous process at a mean load of 90% of installed capacity and an average annual utilization of 78% that can be shut-down very quickly. Given the significant capital intensity of paper machines, they feature a constant daily consumption at a high yearly utilization of about 86%. Moreover, the close interconnection of the various process steps leads to the limitation of a block-wise operation. Starting and shut-down procedures take several hours, resulting in a more restricted suitability for load shifting compared to wood grinders and coating machines (VDE, 2012a). (Boßmann, 2015)

Electric arc and induction furnaces: steel

Electric arc furnaces in steel production are used to recycle scrap and produce secondary steel. The scrap melting process runs at temperatures around 1,800°C, requiring about 0.79 MWh per ton of steel. It takes between 50 and 120 minutes. Once the scrap starts melting (after 5 to 10 minutes), the process cannot be interrupted. Hence, load reduction can only be realised by postponing or omitting the melting process (VDE, 2012a). Klobasa (2007) states that an interruption of the melting process could be attained if financial benefits were sufficiently high. However, if the interruption is prolonged the furnace cools down, reducing energetic efficiency (VDE, 2012a). (Boßmann, 2015)

Electrolysis (wet chemical): copper, zink, etc.

The most suitable process in primary copper and zinc production in terms of load reduction is the electrolysis process which is used to obtain high purity end products. In copper electrolysis, 98% pure blisters are processed to obtain a purity of 99.99% (Lanz et al., 2011). Klobasa (2007) assumes that the load reduction potential of copper electrolysis equals that from aluminium of 25%. (Boßmann, 2015)

Chloralkali electrolysis, chemical industry

Three production methods are used for chlorine alkali electrolysis: mercury, membrane and diaphragm cell. The last one is not suited for DSM activities since load changes may destroy the membrane, however the other two are suitable for load reduction. Load can be reduced to 30% and 40% of installed capacity, respectively (Lindley, 1997). However, reducing load when using the membrane process might reduce product quality. The high share of electricity costs compared to the total product costs makes load reduction particularly attractive (Klobasa, 2007). (Boßmann, 2015)

Cement and raw mill: cement production

Cement production consists of four main steps: raw material feeding, raw material milling, oven process (production of clinker) and cement milling. The second and the fourth step are the most energy intensive (26 kWh/t and 45 kWh/t, respectively (Gutschi & Stigler, 2006). The annual mean utilisation of cement plants is about 74% due to the fact that raw mills run continuously whereas cement mills run only at night and during weekends due to lower electricity prices. According to VDE (2012a), the limited flexibility and storage capacity of raw mills limit load shifting activities to cement mills that can shift their load to weekday hours. Klobasa (2007) also classifies raw mills as shiftable technologies and calculates a shifting potential of 50%. (Boßmann, 2015)

Plug-in Hybrid Electric -/ Battery Electric Vehicles

Plug-in Hybrid Electric (PHEV) and Battery Electric Vehicles (BEV) make use of electricity stored in re-chargeable batteries (mainly Li-Ion), selectively charged by the grid when the vehicle is parked at a charging spot (at home/office or in a public charging point). The characteristics of transportation demand allow fleets of EVs to be used as a flexibility option for the power system in two key operational modes:

- G2V (Grid-to-Vehicle): EVs charging will add to grid load and would require additional generation capacity; charging must be scheduled intelligently in order to avoid overloading the grid at peak hours and to take advantage of off-peak charging benefits, enabling a shifting of the charging times (e.g. through differential cost).
- V2G (Vehicle-to-Grid): the batteries of EVs could be discharged and feed power back into the grid, thereby preventing or postponing load shedding.

Electric vehicles can be a competitive flexibility option enabling a temporal shift of electricity demand for charging because they are expected to be available throughout the day instead of following a rigid charging schedule, based on the fact that vehicles are parked for about 20 to 22 hours in a day.

Electric boiler (Power-to-Heat)

Sanitary hot water boilers (Power-to-Heat) constitute resistance heating equipped with a water tank for hot water provision. Devices of more than 200 l are capable of heating up the maximum daily hot water demand overnight (during eight hours or less). Smaller devices satisfy only reduced hot water demand. If demand exceeds the storage volume, the rated power is sufficiently high to allow for short-term hot water provision (Stadler, 2005). Rated power ranges between two and 20 kW. Given the size of large hot water boilers is determined by the maximum daily demand, load shifting activities of 24 hours can be realised (VDE, 2012b). Smaller devices are limited to 8 hours (Stadler, 2005). (Boßmann, 2015)

Water electrolysis (Power-to-Gas)

Water electrolysis (Power-to-Gas) is used for splitting water into oxygen and hydrogen. Electrolysers consist of an anode and a cathode separated by an electrolyte. Applying a voltage effects that positively charged hydrogen ions migrate to the negatively charged cathode, where a reduction takes place and hydrogen atoms are formed. The electrolysis is a very flexible process with fast start/stop cycling, efficient part-load operation and stand-by mode as well as overload capability (Smolinka, 2014). So, from a technical perspective it is well suited for load management. However, investment is high and thus, high full load hours are needed if hydrogen production costs shall be as low as possible. An advantage of water electrolysis is that hydrogen can be used for specific purposes, e.g. in the chemical industry, in fuel cell vehicles or for the production of methane and methanol. As the last-mentioned processes have to run continuously, hydrogen storage is necessary for decoupling hydrogen production and following production processes.

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