REflex

Analysis of the European energy system

Policy Brief

How to balance intermittent feed-in from renewable energies?

– A techno-economic comparison of flexibility options

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CAES	Compressed Air Energy Storage
FO	Flexibility Option
DSM	Demand Side Management
PtG	Power-to-Gas
PtX	Power-to-X
PV	Photovoltaic Plant
RES	Renewable Energy Sources

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. To achieve the emission reduction targets of between 80 and 95% by 2050 compared to 1990, a fundamental transformation of the energy system is required. The further expansion of renewable energy sources (RES) plays an important role for the decarbonisation pathway. Especially in the electricity sector the increasing share of RES leads to several challenges that are mainly induced by the weather dependency and volatile feed-in of photovoltaic and wind power plants. In an energy system with high RES capacity, situations occur when the electricity generation from RES exceeds total demand as well as situations, when RES production cannot fulfil total demand. The difference between electricity demand and the RES generation is defined as residual load. The residual load duration curve helps to determine the impact of renewables on the electricity system (Figure 1). To compensate the fluctuation of the intermittent RES feed-in, flexibility options are required. Situations with excess electricity generation from RES (negative residual load) as well as situations with RES deficit (positive residual load) need to be compensated in some way. A range of flexibility options exist to provide the necessary compensation in these situations (Figure 1).

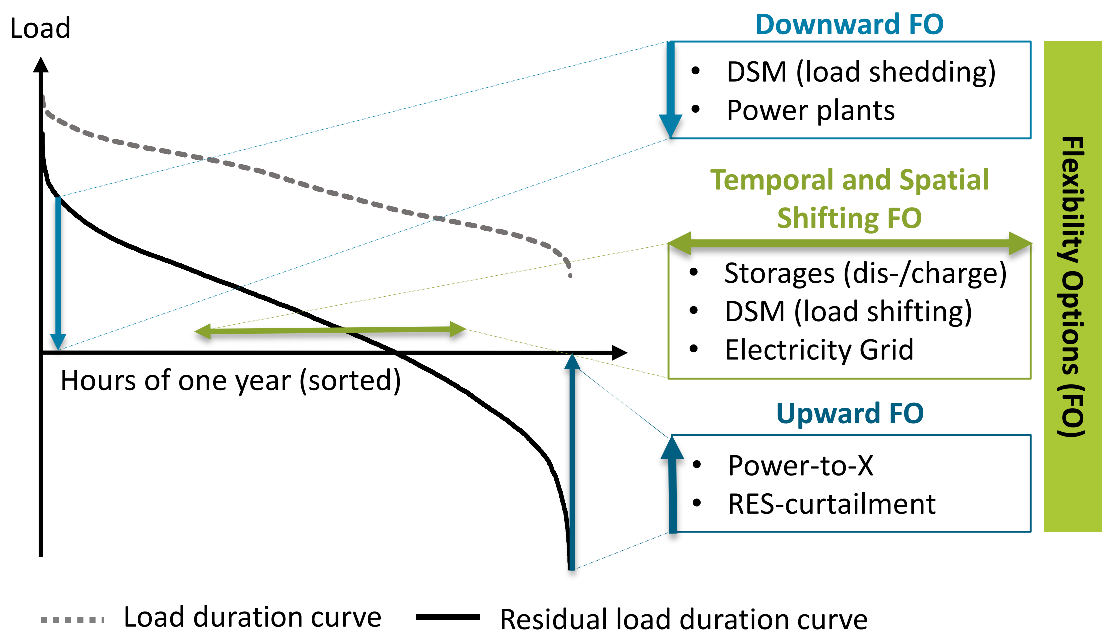

Figure 1: (Residual) load duration curve, categories of flexibility provision and corresponding flexibility options (own illustration)

Flexibility provision can be assigned to three different categories:

- **Downward Flexibility:** Compensating the positive residual load with power plants or load shedding
- **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
- **Upward Flexibility:** Reducing surplus RES feed-in from renewable energy sources by curtailing the excess amount or increasing the demand

Each of these categories comprises different flexibility options. Together with thermal power plants, load shedding applications can provide *downward flexibility* by decreasing load peaks. Load shedding applications decrease their electricity demand without compensating their reduction at another time. *Shifting flexibility* options involve technologies which can be used for spatial and temporal shifting. Electricity grids balance the intermittent electricity generation in one region, by transferring surplus electricity to another region (spatial shifting). Demand Side Management (DSM) regarding load shifting applications and energy storage belong to the category of temporal shifting. Energy storage systems can be charged with excess electricity (negative residual load) and discharged in times with capacity deficits (positive residual load). In contrast, load shifting applications (DSM) reduce their demand in times with high positive residual load and increase it, when the residual load is low or negative. *Upward flexibility* is mainly used in times with negative residual load. Power-to-X (PtX) reduces the negative residual load by using excess electricity for producing other energy carriers, e.g. hydrogen, methane or heat. RES curtailment represents an upward flexibility option as well, given studies that have shown that integrating the available feed-in from RES plants is not always cost efficient from a system perspective (e.g. [1]).

There is a trade-off between the presented flexibility options. Some options are complementary and others compete with and among a category. In particular 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. Within the project REFLEX, a systemically structured overview of flexibility options for the system integration of RES was developed. The following policy brief summarizes the main findings of this assessment. It is based on the corresponding publications [2] and [3], where more detailed results are presented.

The policy brief is structured as follows: Flexibility criteria are defined in section 2.1 based on the technical and economic characteristics of the flexibility options. They form the basis for a comparative analysis presented in section 2.2 - 2.4. The policy brief closes with a conclusion in section 3.

2 Comparison of flexibility options

2.1 Flexibility criteria

To assess which technologies can best provide flexibility, their advantages and disadvantages are described using technical and economic characteristics. The flexibility options are compared with regard to specified criteria commonly used in the literature (e.g. [4], [5]), namely:

- **Activation time** quantifies how much time a specific technology needs to ramp up generation capacity or adjust demand following a request from the system operator. It is also known as the reaction time.
- **Duration of flexibility provision:** Once a demand technology or generators are being used to provide flexibility, it is essential to know how long they provide it. If provision is limited to short time periods, it must be ensured that the use of one technology is followed by the activation of another. Duration may be limited for several reasons that affect mainly DSM technologies and storage systems (e.g. minimum or maximum storage capacity).
- **Number of activations:** The number of activations shows how often a flexibility option can be used to provide flexibility within a certain period. For some technologies, especially in industry, the frequency of load shedding processes is limited to ensure that production targets can still be met. Other appliances have no limits as they are solely intended to provide flexibility and do not have to meet external demand.
- **Activation costs:** If a flexibility option is used, costs occur for its activation [4], resulting from price differences between actual use and originally planned operating schedule. Opportunity costs are also part of the activation costs because they show whether additional costs occur due to providing flexibility. An example is an industrial process that suffers a loss of production if it is required for load shedding for which compensation is required. This compensation is part of the activation costs. Additional investments in a flexibility option are considered part of the initialisation costs, and are neglected in this analysis where the focus is on activation costs only.

2.2 Downward flexibility options

Downward flexibility can be provided by power plants and load shedding applications. Load shedding applications, e.g. aluminium electrolysis or pulp production, decrease demand without compensating the reduction at another time and can thus be used to reduce load peaks. Thermal power plants (in particular highly flexible gas turbines) can adjust their power output within technology-dependent technical constraints and can provide downward flexibility in that way as well [6].

As displayed in Figure 2, load shedding applications show a considerable low activation time (bubble size), 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[1] but have

[1] Figure 2 presents the time for load change activities. If the power plants are shut down and have to make a cold start, the activation time is longer than the one presented in Figure 2.

an almost unlimited duration time. The same applies to the number of activations per day that show stricter limits for load shedding. The underlying processes of load shedding applications can only reduce demand for maximum 3-5 hours to minimise or avoid losses in production. These outages may cause income losses that need to be compensated which is represented by the activation costs. The economic comparison implies that conventional power plants have in general lower activation costs, which are mainly determined by costs for fuel consumption and CO_2-allowances. However, uncertainty is very high for these parameters, and the picture could change if framework conditions like prices for fuel or CO_2 allowances rise.

To sum up, the flexibility potential of conventional power plants for providing downward-flexibility seems more attractive (if investments are neglected) 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.

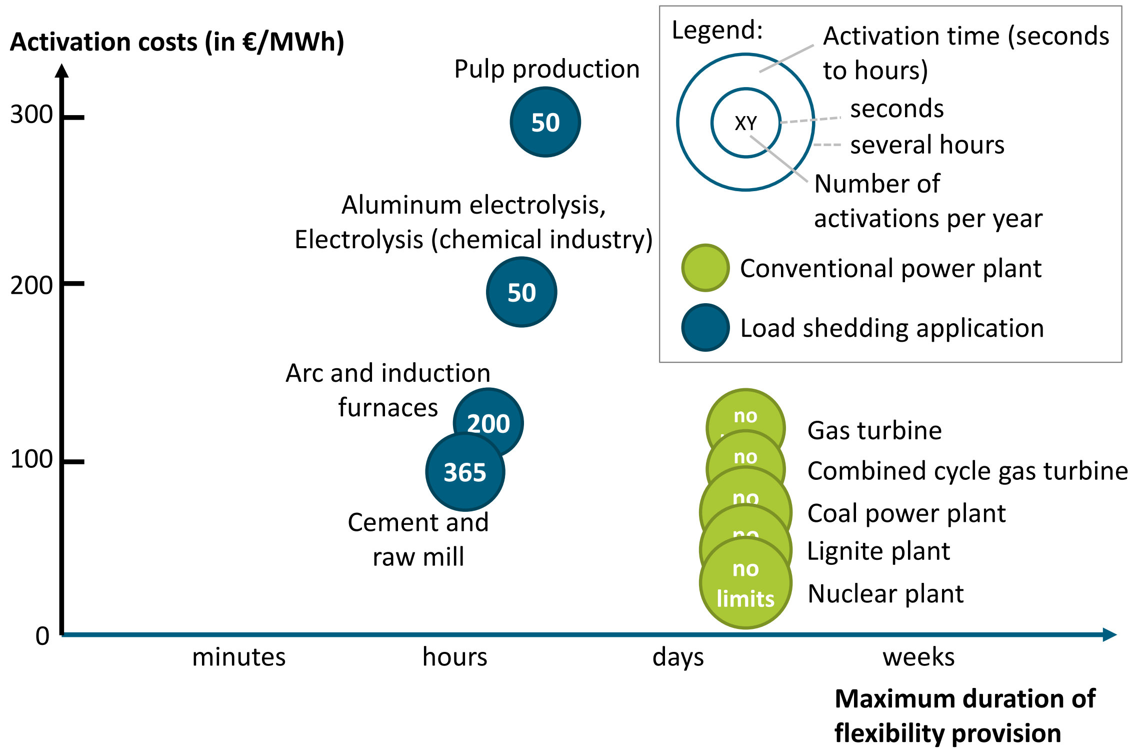

Figure 2: Comparison of downward flexibility options based on the flexibility criteria (own illustration)

2.3 Upward flexibility options

Upward-flexibility options are used in situations with high feed-in of RES and low system demand, so they can help to augment residual load. In general, two concepts can be distinguished: (i) reducing excess feed-in of RES is possible by curtailing RES-surplus or (ii) increasing the demand. Several studies showed that integrating the available feed-in from RES plants completely is not cost efficient from a system perspective (e.g. [1], [7]). Therefore, curtailment of RES represents a flexibility option for upward-flexibility. However, curtailment also means that a potential amount of electricity by RES is not used and the utilization of the RES plant is reduced. By contrast, Power-to-X (PtX) technologies can utilize this excess electricity for further purposes, thereby curtailment can be avoided. In addition, PtX technologies support the decarbonisation of the energy system as the renewable electricity used can substitute fossil fuels. PtX include (amongst others) applications that use electricity for heat (Power-to-Heat: e.g. heat pumps in the residential/tertiary sector, electric smelters in industry) or gas production (Power-to-Gas: e.g. fuel cells as power-to-mobility, electrolysis in industry). PtX technologies are well-suited for consuming excess electricity because they allow a very flexible operation due to low activation times. However, the use of PtX is only profitable if these excess situations occur frequently.

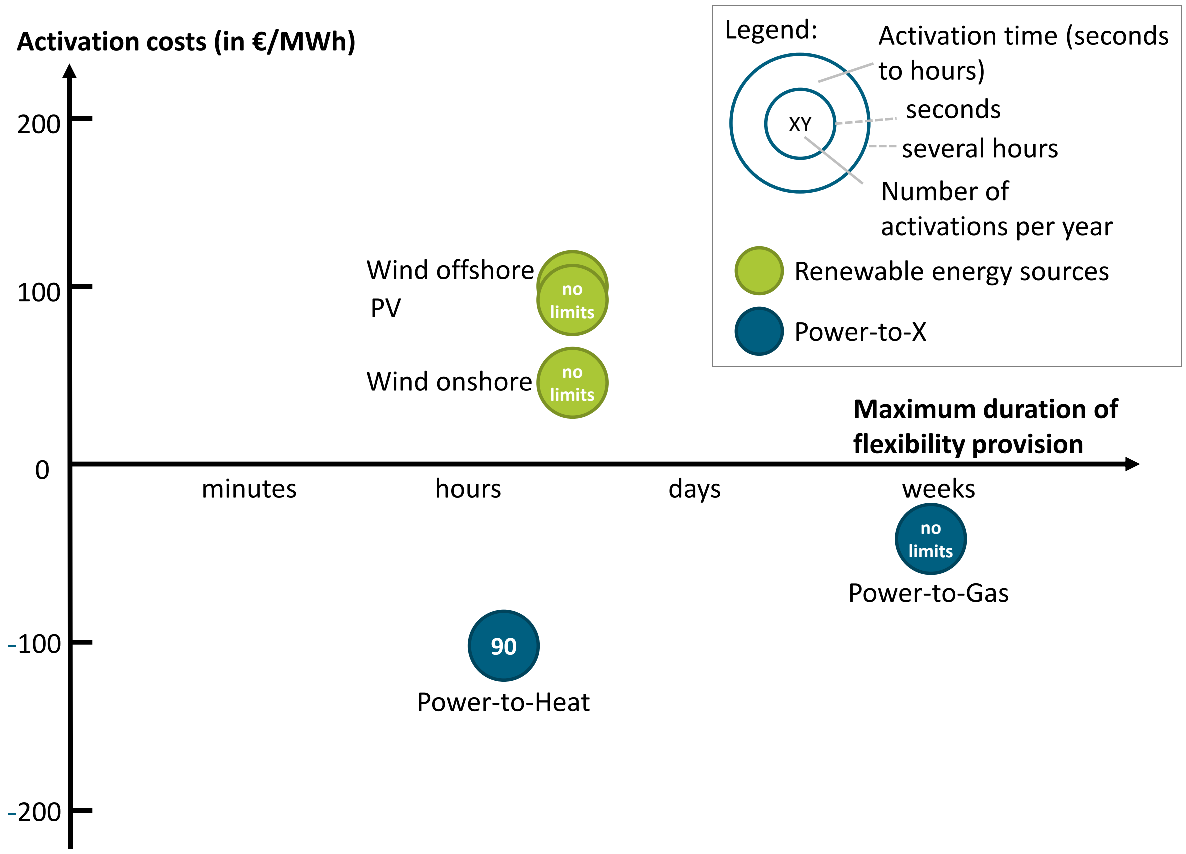

Figure 3: Comparison of upward flexibility options based on the flexibility criteria (own illustration)

Figure 3 illustrates the activation time and costs as well as the maximum duration of flexibility provision for upward flexibility options. In the figure 3, the similar bubble sizes mean that the options shown have same activation time (within seconds or minutes). However, the number of uses per year can differ between the options. Electricity from wind or photovoltaic plants can be limited or curtailed for an indefinite period if necessary, but as periods of wind or solar radiation take in general only some hours [5], the maximum duration of flexibility provision is illustrated accordingly. The demand increase of PtX depends on the need for heat or gas respectively. For electric boilers, the heat demand is affected by the season and weather, but it can be assumed that they are switched on for 2 to 12 hours approximately. As gas can be stored easily in the gas grid, Power-to-Gas plants can be used continuously for long periods of time. In case of RES curtailment, the activation costs amount to the levelised cost of electricity as the operators of RES plants have to waive the revenues that would be possible if were to sell the electricity. The activation costs of PtX technologies are negative because the operators are willing to pay for electricity if they can produce gas or heat for lower costs than the common market price.

2.4 Shifting flexibility options

The group of shifting flexibility options contains technologies used for spatial or temporal shifting. Shifting flexibility is needed in situations with surplus RES feed-in that has to be transferred to other regions or times with positive residual load as well as in situations with positive load peaks that are shifted to times with low or negative residual load. The following technological options exist to exploit the respective flexibility potentials:

- **Electricity grids** can balance intermittent electricity generation within one region by transferring the excess out of their balancing region. Therefore, increasing the capacity of grid lines or their utilization plays a crucial role in spatial shifting. It has been shown that in a fully renewable EU power system, a robust pan-European transmission grid can significantly decrease the residual load [8].
- Temporal shifting uses **energy storage devices** (e.g. hydro pumped storage, compressed air storage, batteries) that can be charged with surplus electricity during times with negative residual load and then discharged in times with positive residual load.
- **Demand Side Management (DSM)** strategies allow for temporal **load shifting** when certain electricity consumers (e.g. white goods, air conditioning, ventilation, heat pumps) reduce their demand at times when the residual load is (highly) positive and increase it when the residual load is low or negative. Demand is shifted and cannot be decreased without compensating this reduction later on.

Figure 4 presents a comparison of the shifting options energy storage and load shifting based on the flexibility criteria defined in section 2.1. While electricity grids and storage technologies are usually not confined in terms of number of shifting activations, Demand Side Management options are usually limited to avoid or minimize a loss of comfort for the consumer (see Figure 4). For the same reason, the maximum duration of flexibility provision is lower for load shifting applications compared to (most) storage facilities. Depending on the storage size, it varies between a few hours and days to weeks. Pumped storage and PtG storage can provide flexibility from several hours to days and up to a week due to higher storages sizes, compared to batteries. The focus of batteries is mainly providing power instead of energy to avoid balance short breakdowns.

The considered load shifting options do not show large differences with regard to activation time. All options can be activated within seconds to minutes. The activation costs of the different options are in the same range as well. All load shifting options profit from price differences in the market. Therefore, the activation cost differ only slightly. They vary between almost zero additional costs (e.g. modern heat pumps which are already equipped with control devices) up to several hundreds of Euros per MWh (see Figure 4)[2].

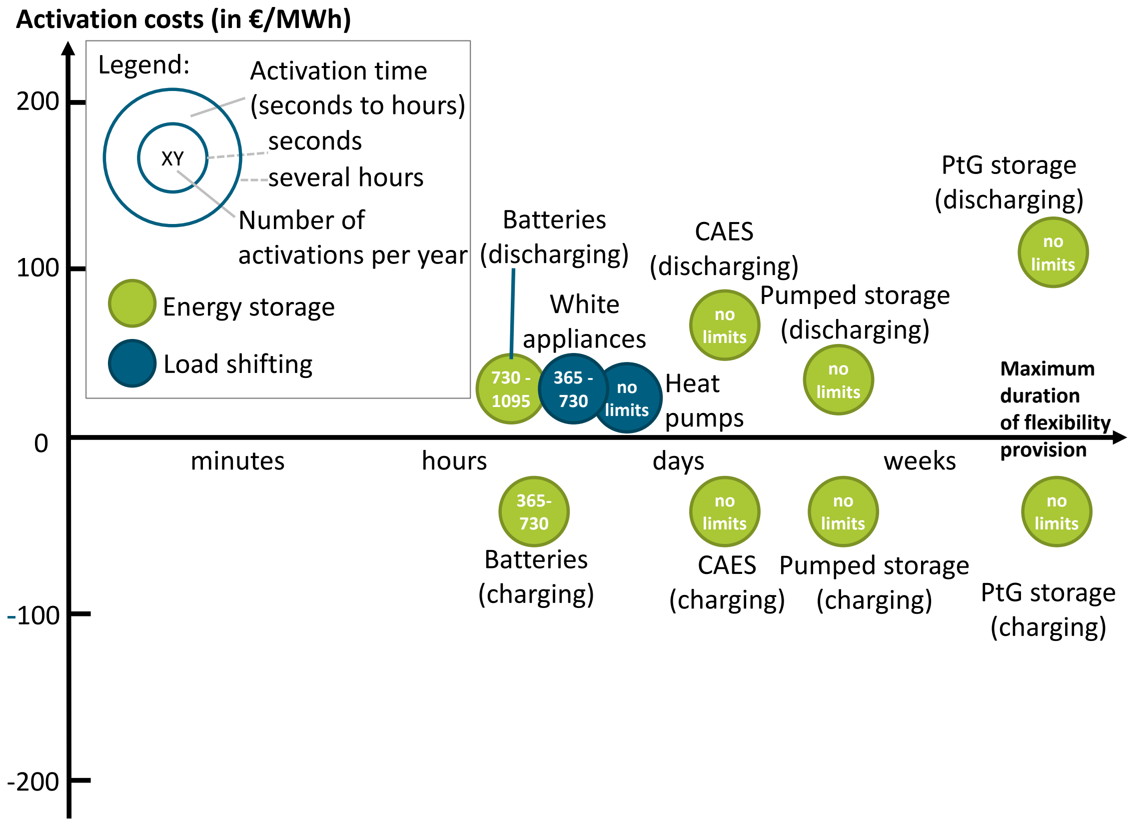

Figure 4: Comparison of shifting flexibility options based on the flexibility criteria (own illustration)

[2] More detailed information about the considered flexibility options and assumptions are presented in [2].

3 Conclusion

In future markets with increasing shares of RES, additional flexibility is needed to maintain system reliability. Therefore, flexibility options are required to balance residual load fluctuations. This document provides a structured overview on flexibility options for system integration of RES, from the perspective of a range of criteria. There is a trade-off between the technologies presented: some are complementary and others compete with and among a category.

Figure 5 qualitatively presents the impact of each flexibility option on the residual load duration curve. Load shifting reduces the residual load in times of high residual load and increase it in times of low residual load. The effect is small as load shifting can only balance short term fluctuations of the residual load due to technical restrictions (e.g. maximum duration of flexibility provision). In contrast, energy storages can transfer larger amounts of energy over hours or days due to bigger storage sizes. Therefore, they are also suitable to balance intermittent RES feed-in within or over days.

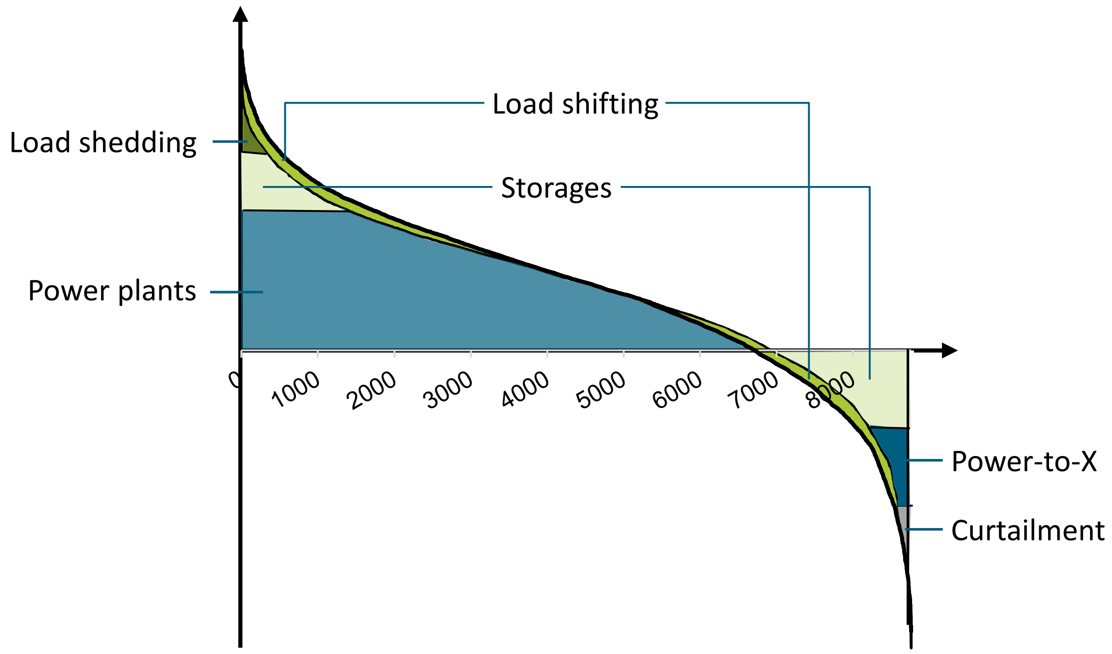

Figure 5: Balancing effect of flexibility options on the residual load duration curve (own Illustration)

Another DSM-option is load shedding, which directly competes with conventional power plants. Conventional power plants seem more attractive to satisfy positive residual load than load shedding applications as they have better values in three of four parameters (costs, the maximum duration of flexibility provision and the number of activations per year). However, some situations will require very immediate flexibility where load shedding has the advantage of a short activation time. These are especially demand peaks, which occur only a few hours a year.

To balance negative residual load, PtX-technologies and curtailment of RES feed-in are suitable as well as energy storage systems. Due to curtailment costs, RES curtailment is more costly than activating a PtX-plant or storage facility. Therefore, PtX or storages are more attractive to balance negative residual load instead of curtailing RES feed-in. However, if investments in new storage facilities or PtX-technologies are needed, it could be cost efficient from a systems perspective to not include every available kWh of RES feed-in but curtail high peaks. In this situation the use of RES curtailment could be the favourable flexibility option.

As an overall result, the analysis reveals that many different flexible technologies with varying characteristics will be potentially available in the future, and a variable mix of technologies will probably be used depending on the respective situation. 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. If some applications compete for the same type of flexibility provision, cost-effectiveness among them will decide which one will prevail. This trade-off between flexibility options will be examined in the model based analysis of REFLEX.

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