stoRE

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Facilitating energy storage to allow high penetration of intermittent renewable energy

Role of Bulk Energy Storage in Future Electricity Systems with High Shares of RES-E Generation

Deliverable 2.2

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Supported by INTELLIGENT ENERGY EUROPE

Acknowledgements

This report has been produced as part of the project "Facilitating energy storage to allow high penetration of intermittent renewable energy", stoRE. The logos of the partners cooperating in this project are shown below and more information about them and the project is available on www.store-project.eu

Final Version, July 2012

The work for this report has been coordinated by Energy Economics Group (EEG)

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List of Abbreviations

AA-CAES	…	(Advanced-) Adiabatic Compressed Air Energy Storage
APG	…	Austrian Power Grid (TSO)
CAES	…	Compressed Air Energy Storage
CCGT	…	Combined-Cycle Gas Turbine
CCS	…	Carbon Capture and Storage
CHP	…	Combined Heat and Power
CO_2	…	Carbon dioxide
$C_{Off\text{-}Peak}$	…	Off-peak electricity generation Costs
$C_{On\text{-}Peak}$	…	On-peak electricity generation Costs
CSP	…	Concentrated Solar thermal Power
$D_{Off\text{-}Peak}$	…	Off-peak electricity Demand
$D_{On\text{-}Peak}$	…	On-peak electricity Demand
DSM	…	Demand Side Management
EC	…	European Commission
ENTSO-E	…	European Network of Transmission System Operators for Electricity
EST	…	Electricity Storage Technology
ETS	…	Emission Trading Scheme
EU	…	European Union
EUA	…	European Union Allowance
FYROM	…	Former Yugoslav Republic Of Macedonia
GW	…	Giga Watt
GWh	…	Giga Watt hour
H_2	…	Hydrogen
HES	…	Hydro Energy Storage (dam- or barrage-hydro power plant)
HFCSS	…	Hydrogen Fuel Cell Storage System
Hz	…	Hertz
ICT	…	Information and Communication Technology
kW	…	kilo Watt
kWh	…	kilo Watt hour
mHz	…	Millihertz
min	…	Minute
MW	…	Mega Watt
MWh	…	Mega Watt Hour
O&M	…	Operation and Maintenance
OCGT	…	Open-Cycle Gas Turbine

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OTC	…	Over-The-Counter
PHELIX	…	Physical Electricity Index on the EPEX SPOT market
PHES	…	Pumped Hydro Energy Storage
P_N	…	Nominal rated power
PV	…	Photovoltaics
RES-E	…	Renewable Energy Sources for Electricity generation
SRMC	…	Short-Run Marginal Costs
t CO_2	…	Ton of CO_2 (i.e. 1000 kg of CO_2)
TSO	…	Transmission System Operator
UCTE	…	Union for the Co-ordination of Transmission of Electricity
WP	…	Work-Package
yr	…	Year

Executive Summary

Within this Deliverable 2.2 (D2.2) of the stoRE project the additional requirements and needs of bulk energy storage technologies (EST) in future energy systems with high penetration of variable / intermittent electricity generation from renewable energy sources (RES-E) are considered. Due to high shares of variable / intermittent RES-E (mainly wind) generation, future electricity systems are, on the one hand, increasingly “stressed” on several time scales in both dimensions “amplitude” and “frequency” of extreme events in system operation.

At first, possible future challenges of bulk EST due to high shares of variable RES-E generation are summarized. Some RES-E technologies (e.g. hydropower, bio-energy, geothermal etc.) are dispatchable, i.e. they can be called upon to operate at any given time and can be managed like conventional generation technologies, and can therefore be easily integrated into the electricity system.

However, the ongoing integration of large amounts of non-dispatchable, i.e. very variable and less predictable wind and solar (photovoltaic, PV) power into the European electricity system induces more frequent and uncertain price fluctuations at the competitive spot market due to changing in-feed. This additional volatility in the electricity generation also increases the demand for control reserves and also leads to higher balancing needs.

Nowadays, fluctuations in RES-E generation are compensated by existing conventional (fossil-fuel) power plants, which operate in turndown mode (part-loading). However, increasing part-loading of the conventional power plants lowers their efficiency and results in higher operation and maintenance costs and thus reduced lifetimes. Additionally, the full-load hours of these power plants decrease dramatically in the future due to high RES-E generation. The decrease of the annual full-load hours has the consequence of an increase of electricity generation costs. Combined with the decreased efficiency and lifetime due to increased need to run part-loaded, this has a significant negative effect on the economics of conventional power plants. Furthermore, a part of the existing conventional power plants has to be shut down in the near future due to their age, which increases the stress to balance electricity systems.

Since bulk EST rely for their economic viability on the spread of the electricity price at different points in time and are also able to provide control reserves, the increasing deployment of non-dispatchable RES-E technologies also favours the deployment of bulk EST. Though increasing RES-E generation might also have a negative economic effect for bulk EST. The so-called merit order effect has the potential to lower the arbitrage between peak and off-peak prices in the long-term, which results from the fact that the merit order curve is generally more convex in periods with higher demands.

Also the European emission trading scheme (ETS) may lead to a similar effect as the price gap between gas and coal / lignite decreases with the introduction of additional CO_2 prices since lignite and coal have higher specific CO_2 emissions. Given that coal / lignite power plants are generally base load and gas power plants are generally peak load power plants, the decreasing price gap also means that the ETS may lead to a more homogeneous merit order and a reduction of the electricity price spread between base and peak load. However, the impact of the merit order effect and the ETS are strongly dependent on the existing power plant mix in the electricity system.

In the second part of the report, the requirements / needs of and opportunities for bulk EST in the different market segments of the electricity market on different time scales are summarized. Additionally examples on the price volatility and on the operation of the different markets are given.

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Besides the primary control market, were very fast response times are needed, bulk EST can significantly contribute in all described electricity markets in general. However, with their potential to generate large amounts of electricity within short time periods, bulk EST fit especially well for the short-term markets, e.g. secondary and tertiary control as well as intraday markets, which also offer good opportunities for price arbitrage.

The third part of the report provides an overview of other technology options which increase the flexibility of future energy systems, since the storage capacities of bulk EST are limited and, therefore, only partly can contribute to balance the fluctuations caused by variable RES-E feed-in. Therefore, especially for longer periods with little RES-E feed-in (e.g. meteorological inversion) and / or times with high RES-E generation fluctuations, additional storage capacities and / or other technology options which increase the flexibility in future energy systems will be needed to balance the future electricity system.

These other technology options include dispatchable conventional power plants, which, however, suffer from multiple effects already described before. Not all dispatchable power plants provide the same amount of flexibility (i.e. high power ramp rates). E.g. gas turbines offer high ramp rates whereas coal and other base load power plants generally have lower flexibility. By curtailing of the variable output of RES-E generation (e.g. for wind, PV etc.) or by adjusting their remuneration rules also RES-E generation could provide additional flexibility.

The reduction of the amount of heat demand driven electricity generation in combined heat and power plants (CHP) by introducing heat storages, heat pumps and electric heat boilers also increases the flexibility potential of electricity systems. Demand side management (DSM) also has the potential to ease problems of the electricity system with increased variable RES-E generation. Though, this flexibility potential will depend on consumer engagement as well as economic incentives.

Another technology option is transmission grid extension offering the opportunity of widening the balancing area. This means, the flexibility provision for an electricity system does not necessarily have to be covered inside the footprint of a single country / market region. This also reduces the stress on the electricity system and uncertainty of variable RES-E generation balancing through exploiting greater geographical diversity. This possible contribution of future transmission corridors and also direct benefits of bulk EST implementation in electricity systems with high variable RES-E is analysed and discussed in detail in Deliverable 2.3 (D2.3) of the stoRE project.

1 Introduction

1.1 General

The information and discussions presented in this report are part of the European project stoRE (www.store-project.eu). stoRE aims to facilitate the realization of the ambitious objectives for high penetration of variable / intermittent renewable energies in the European grid by 2020 and beyond by unblocking the potential for energy storage technology implementation. Energy storage, as part of an integrated approach including grid infrastructure reinforcement and demand management, brings advantages to existing and future electricity systems. Moreover, it helps accommodate higher percentages of variable / intermittent renewable energy by balancing supply and demand and improving power quality.

Within work-package 2 (WP2) of the stoRE project, a collection, evaluation and update of information about the status and future potential of energy storage technologies takes place, setting the foundations for the work to be carried out in the rest of the project.

This document, Deliverable 2.2 (D2.2), summarizes the requirements of bulk energy storage technologies in future energy systems with high penetration of renewable energies for electricity generation (RES-E). After a brief introduction into (bulk) energy storage and their interrelationship with the integration of RES-E, this report is structured into three main parts:

- Section 2 identifies possible future challenges of bulk electricity storage technologies (EST) due to high shares of variable RES-E generation.
- Section 3 of this report provides an overview of the different market segments in the electricity market on different time scales and discusses the requirements / needs and opportunities of bulk EST in the different market segments in detail.
- Section 4 finally presents the limits of bulk EST as well as other technology options to increase flexibility in future energy systems.

1.2 Bulk Energy Storage & Renewable Energies

In electricity systems, supply and demand have to be balanced in real time. Therefore, every electricity system requires sufficient power plants[1] to operate to be able to meet maximum electricity demand. Electricity demand, furthermore, fluctuates on a temporally basis and maximum electricity demand is reached only some hours per year (average demand ~60 % of maximum demand). To overcome these fluctuations, flexible generation (gas turbines, combined-cycle gas turbine (CCGT), etc.) and load management technologies in combination with (indirect)[2] electricity

[1] And / or sufficient interconnection capacities to other electricity systems accompanied with sufficient power surplus.
[2] Indirect EST store electrical energy in mechanical (potential, kinetic etc.) or chemical energy and convert it back into electricity when needed, cf. Deliverable 2.1 (D2.1) of the stoRE project.

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storages, such as pumped hydro energy storage (PHES), have been used to balance the electricity system (see section 2 for more details).

The growth of distributed generation in general, and the increasing deployment of variable / intermittent renewable electricity generation technologies like wind and solar photovoltaic (PV) in the electricity system in particular, is changing the way electricity systems have to be operated and managed in the future. Due to high shares of variable / intermittent RES-E (mainly wind) generation, future electricity systems will be increasingly "stressed" on several time scales in both dimensions "amplitude" and "frequency" of extreme events in electricity system operation.

Bulk energy storage technologies are expected to be one of the key enabling technologies for the integration of large amounts of variable / intermittent RES-E generation. In particular, the ability to quickly discharge large amounts of stored electricity or to reduce loads during certain points in time throughout a day (i.e. output smoothing) can mitigate many challenges which arise with high shares of variable / intermittent RES-E generation in the electricity system. Further on, bulk EST could play an important role in optimising the physical and financial functioning of electricity markets and the corresponding commercial energy trading activities.

1.3 Other Energy Storage Technologies

In the stoRE project the focus of analysis and discussions is set predominantly on bulk energy storage technologies. It is, however, worth mentioning, that the deployment and development of other (non-bulk) energy storage technologies, like battery systems and flywheels, also induces benefits for the electricity system. However, since their electricity storage capacities are technically and / or economically limited[3] in future electricity systems with high shares of variable / intermittent RES-E generation their major role will be in short-term applications (e.g. output smoothing within seconds, etc.) and applications on low voltage levels. These applications, where bulk EST cannot be used due to their relatively high response times or high voltage levels will form a niche market for other EST.

In order to provide a complete picture of energy storage options, Deliverable 2.1 (D2.1) of the stoRE project also provides a brief overview of other (non-bulk) EST that are outside the scope of the stoRE project.

[3] Whereas hydrogen fuel cell systems and electric vehicles (see Deliverable 2.1 of the stoRE project) may also be future options for large-scale electricity storage.

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2 Challenges due to high Shares of variable RES-E Generation

2.1 Overview

The electricity generation from renewable energy sources (RES-E) has increased significantly in the last years in the European Union (EU). One major reason for this development are the national promotion strategies (e.g. feed-in tariffs, quota-based tradable green certificates, investment grants, etc.) which were triggered by the different directives and policy targets of the European Commission (EC) (e.g. 20-20-20 targets). Without these promotion incentives, RES-E technologies generally cannot compete with conventional generation technologies yet.

However, the increasing deployment of RES-E has significant impacts on both electricity prices and ancillary service requirements (e.g. primary-, secondary- and tertiary control reserve). Both of them form a key framework for the application of EST. Some major challenges in this respect are described in the following sections.

2.2 Increasing Price Volatility and Need for Reserve Capacities

Some RES-E technologies are dispatchable, i.e. they can be called upon to operate at any given time and can be managed like conventional generation technologies. Dispatchable RES-E technologies include geothermal, hydropower, bio-energy and, to some extent[4], also concentrated solar thermal power plants (CSP). The remaining RES-E technologies wind, solar photovoltaics (PV) and wave / tidal energy are strongly dependent on the availability of the renewable energy source, i.e. the meteorological conditions. In general, the output of these technologies is very variable and less predictable. Therefore, these RES-E technologies are non-dispatchable. (IEA, 2011a)

While PV fluctuations have a more regular pattern (e.g. no generation at night, output does not drop to zero under cloud cover), wind and wave power are the most irregular RES-E sources, especially in smaller areas. Their power output may change very rapidly and for longer time periods with only little observable pattern and predictability. Tidal power, on the other hand, is the most regular non-dispatchable RES-E source, the pattern of its availability (i.e. gravitational force of the moon) is replicated regularly from period to period. (IEA, 2011a)

The ongoing integration of large amounts of non-dispatchable wind and solar power into the European electricity system therefore also induces more frequent and uncertain price fluctuations on the wholesale electricity spot market due to varying feed-in of RES-E generation. Depending on the available wind speed and solar irradiation, the residual load[5] varies, e.g. if the wind speed is high a cheaper plant sets the price on the wholesale electricity market. This means that the

[4] Depending on the availability and size of the integrated thermal storage.

[5] The residual load is the load which has to be covered by the conventional power plants, i.e. the total load less the generation of the RES-E technologies.

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wholesale electricity price depends strongly on the meteorological conditions (cf. section 2.3). (Gatzen, 2008)

In this context, Figure 1 shows an example on the variation of RES-E generation in Germany in the year 2020[6]. The yearly share of RES-E generation on the total electricity demand (black line) is about 47 % in 2020. Especially in January the monthly average (green line) is very high, which is caused by high wind feed-in in this month. The weekly variations (red line) are very distinctive in the last quarter of the year, where RES-E shares between 20 % and 70 % are reached. (IWES, 2009)

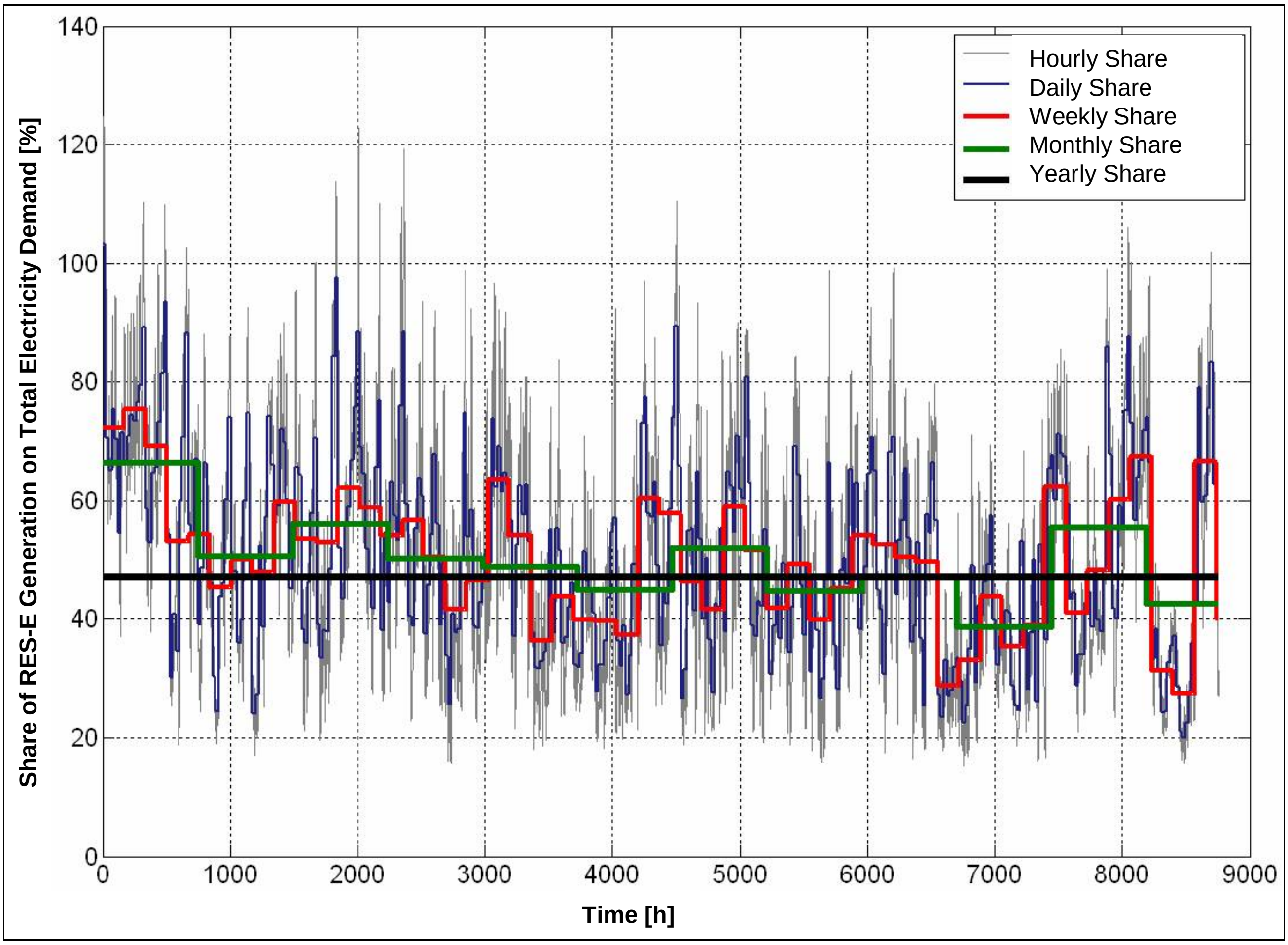

Figure 1: Share of RES-E generation on the total electricity demand in Germany 2020 (Source: IWES, 2009)

As an example for the relevance of the variations in RES-E generation for PHES operation schemes, Figure 2 shows a simulation of the management of the upper reservoir of the Austrian PHES Kaprun in the year 2020. It can be seen that with the additional extensions of the PHES also the frequency and amount of level variations of the upper reservoir increase significantly.

Further on, this additional volatility in electricity generation also increases the demand for control reserves (primary, secondary and tertiary, see also chapter 3 and D2.1), which are needed for frequency control (i.e. for balancing supply and demand) in the electricity transmission system.

[6] Based on meteorological data of the year 2007 and installed RES-E capacities of the "Stromversorgung 2020" scenario of the Bundesverband Erneuerbare Energie e.V. (BEE, 2009).

With large amounts of non-dispatchable RES-E technologies in the electricity system, the influence of forecast errors on the demand of control reserves increases. The needed control reserves can be either positive or negative since the actual feed-in of RES-E generation technologies either can be higher or lower than the forecast. (Gatzen, 2008)

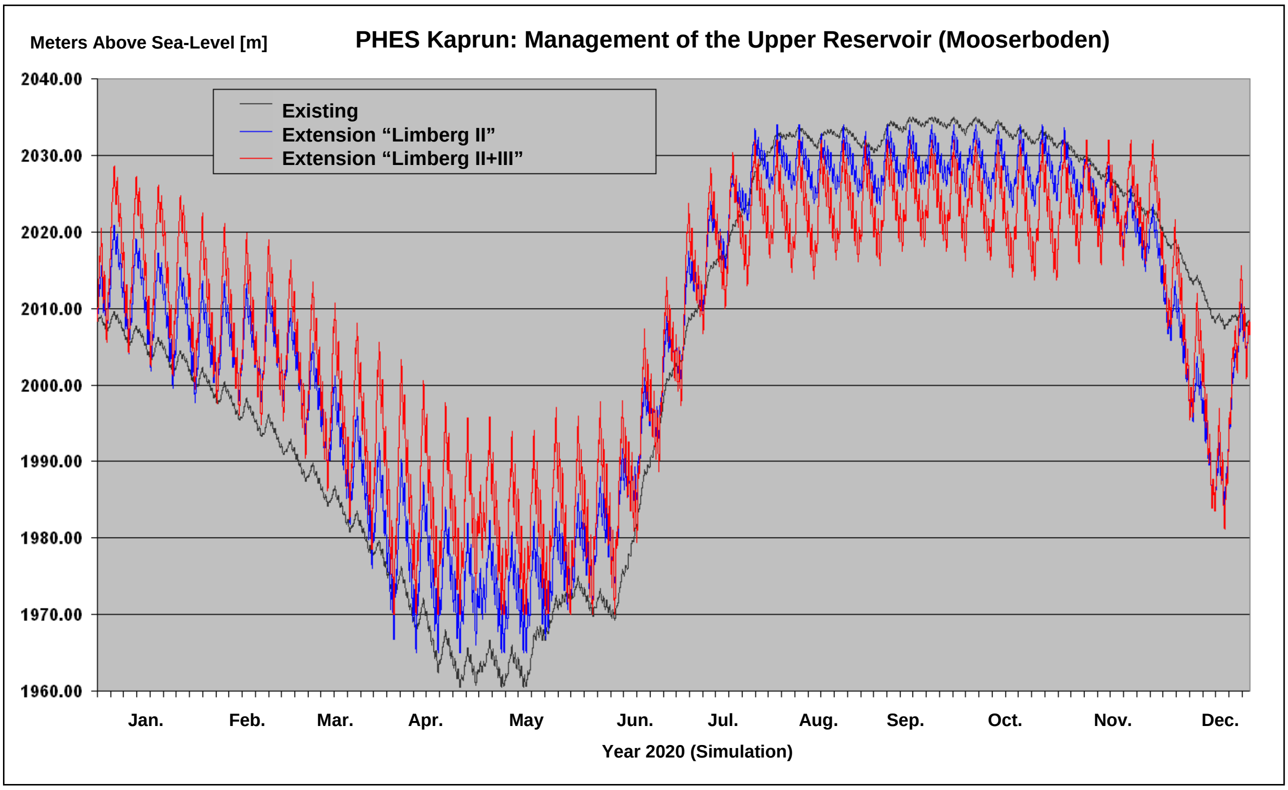

Figure 2: Simulation of the management of the upper reservoir of the PHES Kaprun (AT) in the year 2020 (Source: Ottendörfer, 2010)

Nowadays, fluctuations in RES-E generation are mainly compensated by existing conventional (fossil-fuel) power plants, which operate in turndown mode (part-loaded)[7]. Therefore, the rising RES-E feed-in will also lead to higher balancing demand for conventional power plants (i.e. higher part-loaded time periods) and this decreases their efficiency. The efficiency decrease due to part-loading can be up to 20 % for combined-cycle gas turbines (CCGT) when operating at 50 % of their nominal rated power (P_N). Table 1 shows these typical efficiency changes of different technologies due to part-loading at 50 % of P_N. The efficiency decrease also results in higher specific emissions for fossil fuel based generation (see also section 2.4).

Increased flexibility requirements for the conventional power plants and the resulting load following also imply higher operation and maintenance costs (O&M costs) and reduced lifetimes of the power plants.

[7] "*Part-loading refers to the operation of a power plant at a power output level lower than the nominal rated power, where the latter stands for the maximum technical capability of the (used) machinery as certified by the responsible licensing authority. The capability to run power plants in part-loading is a fundamental characteristic of dispatchable generation technologies because their output is controllable in real time*" (EURELECTRIC, 2011).

Table 1: Typical efficiency change of different electricity generation technologies due to part-loading at 50 % of P_N (Source: EURELECTRIC, 2011)

Technology	Efficiency Change due to Part-loading at 50% of P_N
CCGT	-20 %
Coal	-10 %
Gas	-5 to -10 %
Diesel	~0

Because of steadily growing shares of RES-E generation technologies with low marginal electricity generation costs (especially wind and PV) in the electricity system, the full-load hours of conventional power plants will decrease dramatically in the future. As an example for this decrease, Figure 3 shows the residual load in Germany in 2007 and scenarios for 2020, 2030 and 2050. It can be seen, that beginning with the year 2020 the maximum full-load hours of conventional (base load) power plants will be lower than 8760 h/yr. By 2050, the maximum full-load hours of conventional generation plants will have decreased to about 6200 h/yr. The decrease of the annual full-load hours has the consequence of an increase of electricity generation costs. Combined with the decreased efficiency and lifetime due to increased needs to run part-loaded, this has a significant negative effect on the economics of conventional power plants. Furthermore, a part of the existing conventional power plants has to be shut down in the near future due to their age. This increases the stress for balancing the electricity system in addition.

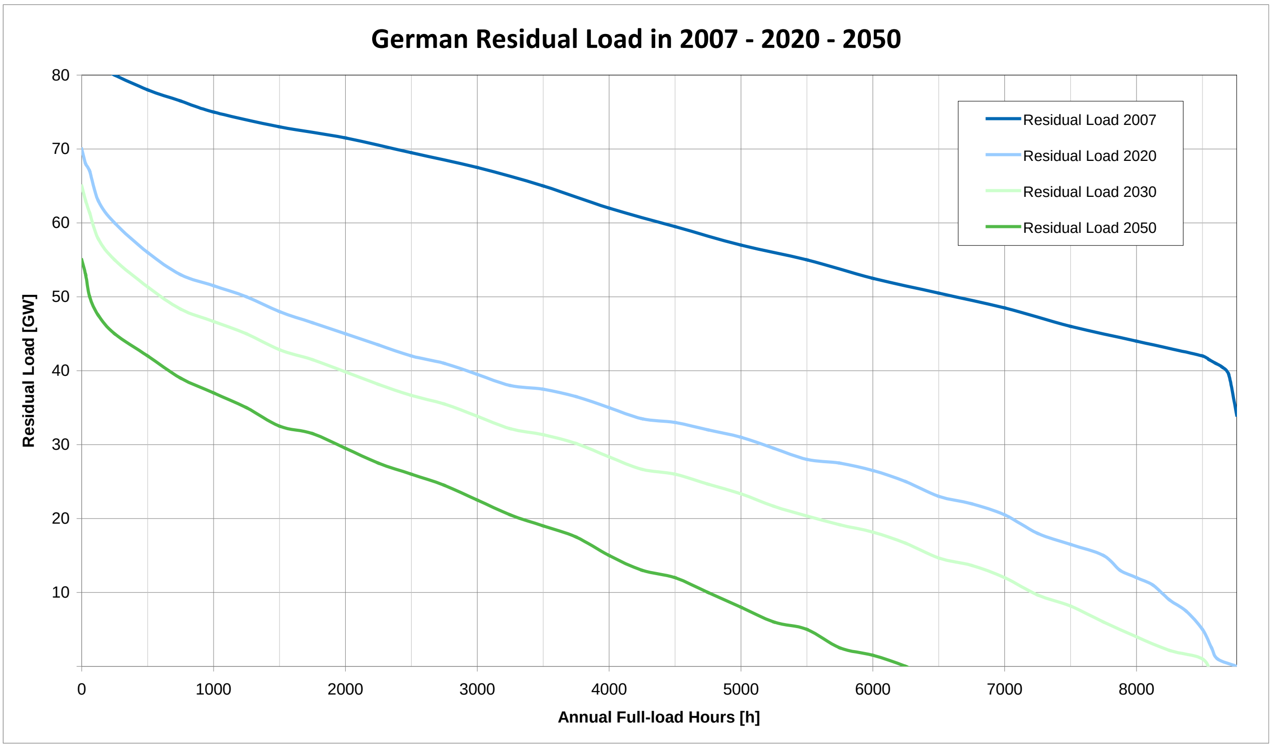

Figure 3: German residual load in 2007, 2020, 2030 and 2050 (Source: based on Körbler, 2011)

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Since bulk EST rely on the price spread of wholesale electricity markets and are also able to provide control reserves, the increasing deployment of non-dispatchable RES-E generation technologies also favours the deployment of bulk EST in general. Though, increasing capacities of solar PV could lead to a price damping effect in the midday peak and therefore lowering of the available price margin. This is already observable in the German electricity market in the years 2010 and 2011. (Steffen, 2012)

2.3 The Merit Order Effect

Besides the effect of additional volatility of the wholesale electricity price described above, stringent RES-E generation can also have the effect of lowering the arbitrage between peak and off-peak prices in the long-term. This effect is called the merit order effect (cf. Sensfuß et al, 2008) and results from the fact that the merit order curve is generally more convex in periods with higher demands.

Figure 4 shows an example of a merit-order of short-run marginal electricity generation including the on- and off-peak electricity demand ($D_{On\text{-}Peak}$ / $D_{Off\text{-}Peak}$) and the resulting marginal generation costs ($C_{On\text{-}Peak}$ / $C_{Off\text{-}Peak}$). It can be seen that the introduction of additional non-dispatchable RES-E generation with low short-run marginal generation costs (e.g. wind and PV) shifts the merit-order curve to the right (green curve). This implicates that on- and off-peak demand are now intersecting the marginal electricity generation curve in a section with a smaller incline than prior to the introduction of additional generation. Hence, the resulting cost spread between $C_{On\text{-}Peak}$ and $C_{Off\text{-}Peak}$ is smaller than prior to the introduction of additional non-dispatchable RES-E generation.

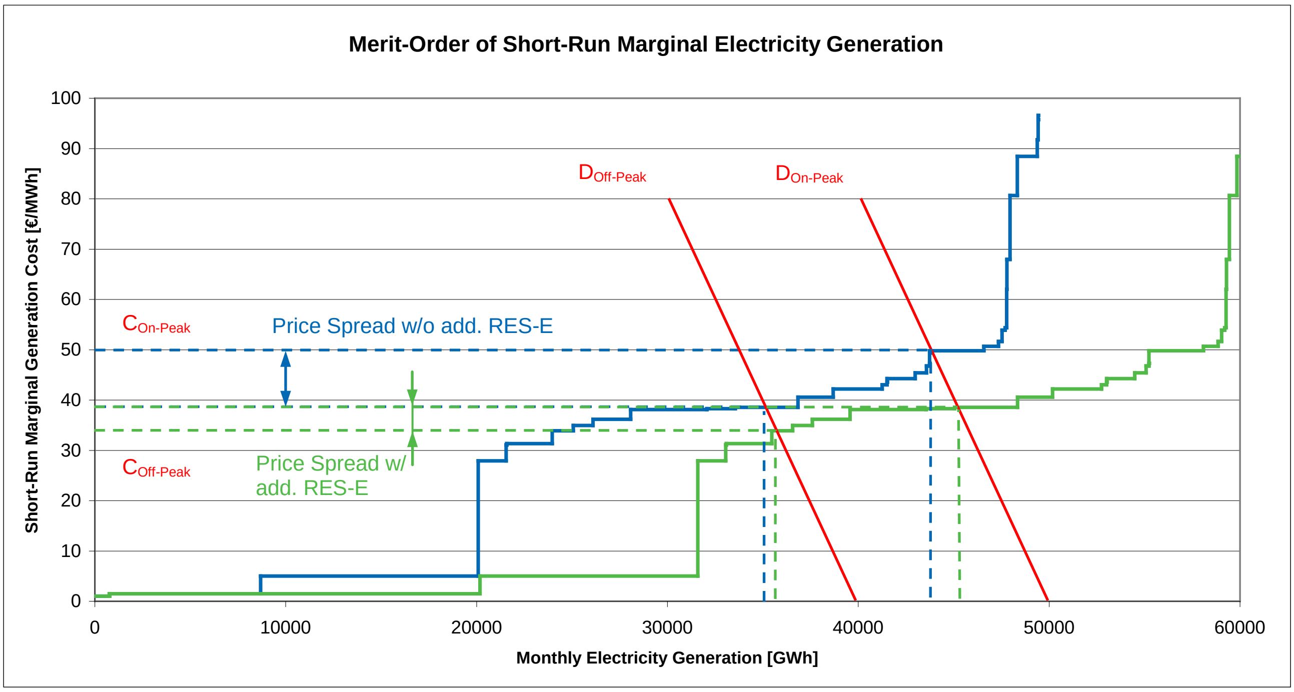

Figure 4: Wholesale electricity price spread between on-peak and off-peak in the merit-order curve (Source: EEG)

Since electricity price arbitrage is one of the major sources of income for electricity storage operators (cf. D2.1), the merit order effect could have a negative impact on the economies of electricity storage. However, this impact strongly depends on the existing power plant mix in an electricity system. In systems with very high shares of RES-E generation (> 40 %) for instance, situations can occur, where RES-E feed-in exceeds off-peak demand and, therefore, RES-E driven pumping energy is available almost for free. (Steffen et al, 2011)

2.4 Compression of Merit Order Curve due to Emission Trading Scheme

The European emission trading scheme (ETS) came into force in 2005 and obliges the majority of power and heat conversion plants to take part in the new emission trading system. For each tonne of CO_2 the plant emits the plant operator has to own a certificate (EU-Allowance, EUA), which can be traded on the market. Those operators having not enough allowances to cover their emissions have to pay a dissuasive fine for each excess tonne emitted. (EC, 2005)

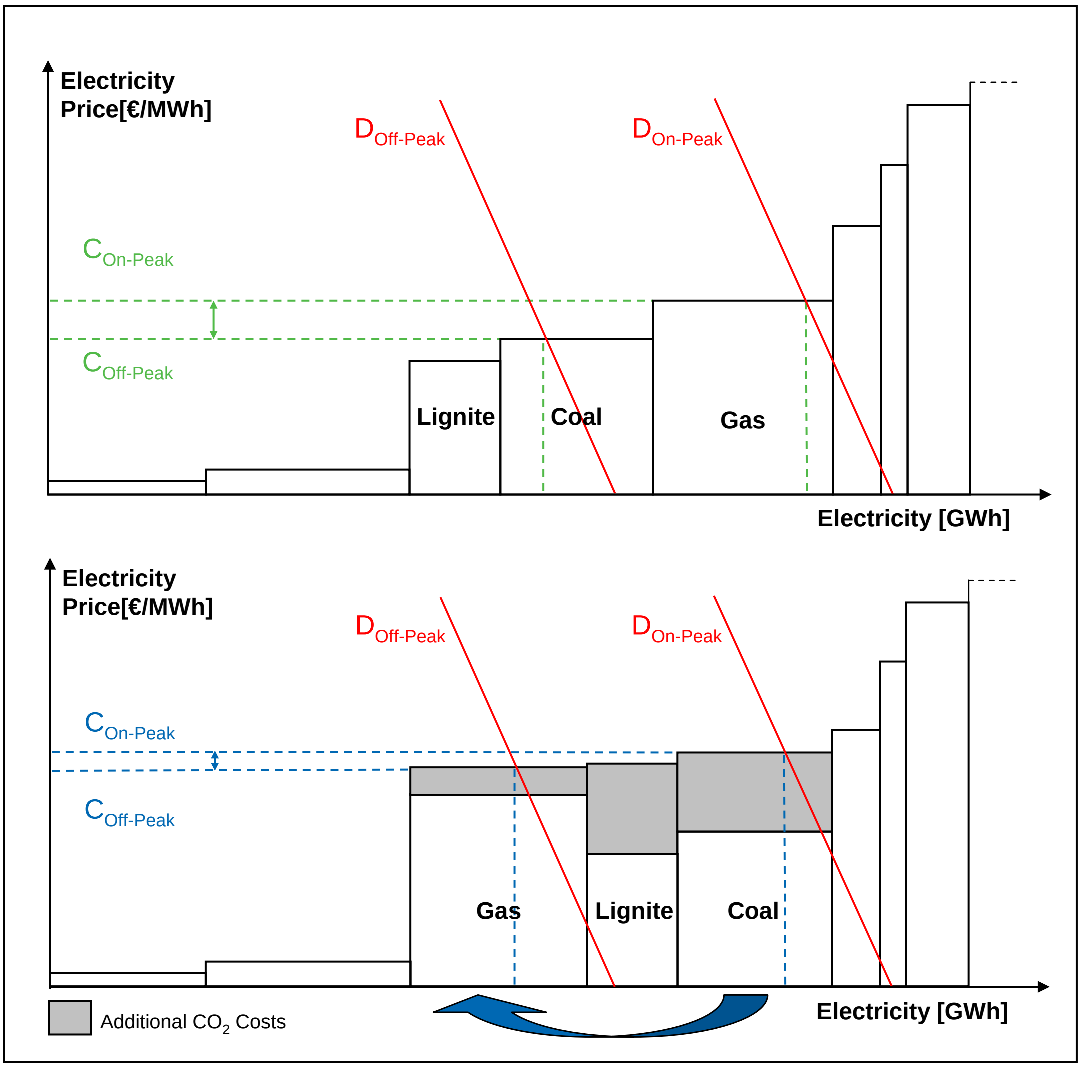

Figure 5: Illustrative example of the wholesale electricity price spread between on-peak and off-peak in the merit-order curve with (top) and without additional CO_2 costs (bottom) (Source: EEG)

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Therefore, the ETS increases the power generation costs of carbon based power generation technologies, e.g. the variable costs of power generation increase the more CO_2 is emitted. This can be seen in Figure 5, where a simple illustrative example of a merit-order of short-run marginal electricity generation is presented. The figure shows that the wholesale electricity price gap between gas and coal / lignite decreases with the introduction of additional CO_2 prices, since lignite and coal have higher specific CO_2 emission factors[8]. Given that coal / lignite power plants are generally base load and gas power plants are generally peak load power plants, the decreasing wholesale electricity price gap in that example also means that the ETS leads to a more homogeneous merit order and a reduction of the wholesale electricity price spread between base and peak load. In the shown example, gas becomes cheaper than coal and lignite and is shifted to the left in the merit-order curve (Figure 5 bottom). However, also the impact of the ETS depends of course on the existing power plant mix in an electricity system. (Gatzen, 2008)

Concluding, the "compression" of the merit order curve due to the ETS may therefore also have a similar negative effect on the economics of bulk EST as the merit order effect described before.

[8] Specific CO_2 emission factors [t CO_2/MWh]: Natural gas 0,37, lignite 0,94 and coal 0,85 (IEA, 2011b).

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3 Requirements / Needs and Opportunities of Bulk Energy Storage Technologies in the different Market Segments of the Electricity Market on different Time Scales

3.1 Overview

The electricity market can be split into different sections in terms of their time scales and how close their products are operated to real time. Figure 6 gives an overview of these different market segments. Generally, electricity is either traded anonymously on power exchanges or based on bilateral contracts (i.e. over-the-counter, OTC).

The largest share on electricity trades, some 80 – 85 %, is usually accounted for by long-term contracts (weeks to months in advance) in the futures / forwards market. About 15 – 20 % of electricity trades take place in the day-ahead market (days to weeks in advance, also called spot market), with a modest 2 – 5 % accounted for in the intraday and control power market operation. (Haas et al, 2006)

In the following sections, the different electricity market segments on different time scales and the requirements / needs and opportunities of bulk EST in the different market segments are discussed in detail.

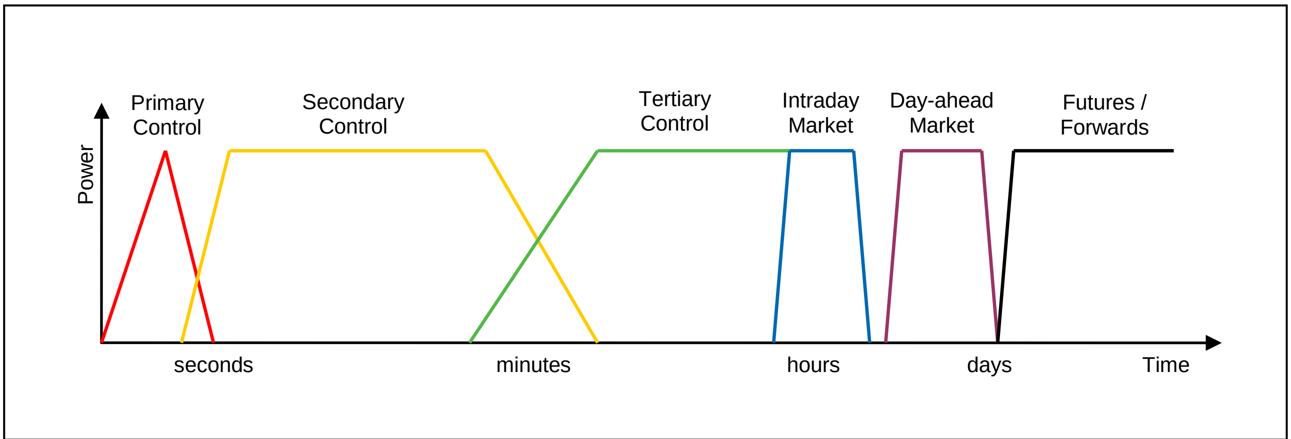

Figure 6: Overview of the different market segments in the electricity market (Source: UCTE, Nordel, EMD, EEG)

3.2 Control Power Market

3.2.1 Description of Primary, Secondary and Tertiary Control

The load-frequency control actions in a synchronous electricity supply area are performed in different successive steps, each of them with different characteristics and qualities, and all depending on each other (see Figure 7 below). In the following, the three different kinds of control power markets are described.

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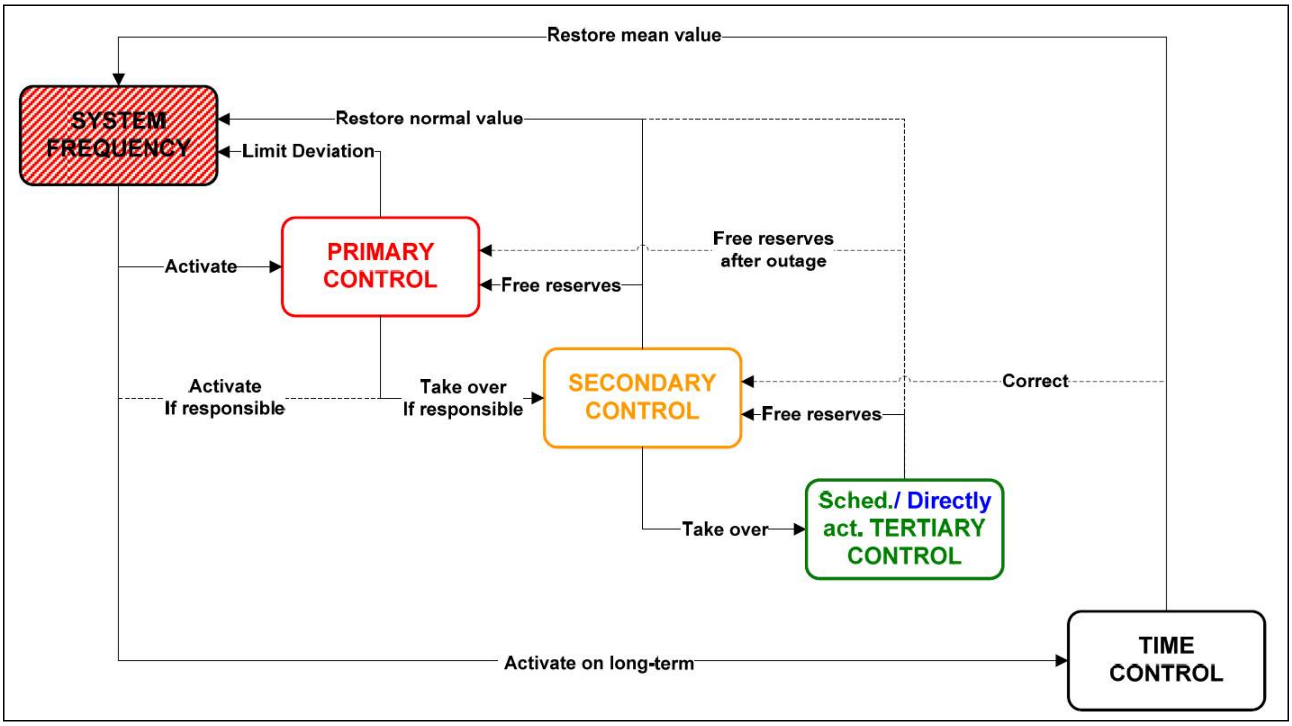

Figure 7: Load-frequency control scheme and actions starting with the system frequency in the synchronous area (Source: ENTSO-E, 2011)

- **Primary Control**

Primary control maintains a balance between generation and consumption (demand) within a synchronous area[9]. It stabilises the system frequency at a stationary value after a disturbance or incident in the time-frame of seconds, but without restoring the system frequency to the nominal frequency of 50,000 Hz and the power exchanges to their reference values. The overall primary control reserve for the synchronous area is based on a reference incident (i.e. maximum instantaneous power deviation) and is 3000 MW in the UCTE region.

Adequate primary control depends on generation or load resources made available to the TSOs of the interconnected synchronous area. However, each TSO has to contribute to the correction of a disturbance in accordance with its respective contribution coefficient[10] to primary control.

Primary control is started a few seconds after the incident, "*the deployment time for 50 % or less of the total primary control reserve is at most 15 seconds and from 50 % to 100 % the maximum deployment time rises linearly to 30 seconds*". Primary control power has to be delivered until the power deviation is completely offset by the secondary and tertiary control reserves (with a minimum of 15 minutes delivery capability). Primary control reserves must be available continuously without interruption and "*fully activated in response to a quasi-steady-state frequency*

[9] Synchronous area corresponds to the area of the former Union for the Co-ordination of Transmission of Electricity (UCTE), i.e. Austria, Belgium, Bosnia-Herzegovina, Bulgaria, Czech Republic, Croatia, Denmark (West), France, FYROM, Germany, Greece, Hungary, Italy, Luxemburg, Montenegro, Nederland, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain and Switzerland, now part of the European Network of Transmission System Operators for Electricity (ENTSO-E).

[10] The contribution coefficient is calculated annually: electricity generated within a control area divided by the sum of electricity generation in all control areas of the synchronous area.

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deviation of +/- 200 mHz or more". Further on, the accuracy of the local frequency measurement has to be below +/- 10 mHz. (ENTSO-E, 2011)

Primary control reserve is defined in a symmetric manner, which means that a bidder has to provide for each MW of capacity for down-regulation simultaneously one MW of capacity for up-regulation.

- **Secondary Control**

Like primary control, also secondary control maintains a balance between generation and consumption and stabilizes system frequency. Whereas all control areas in the interconnected synchronous UCTE area have to provide mutual support to primary control reserve, only the control area / block affected by a power imbalance is required to undertake (automatic) secondary control action for correction.

As described before, primary control re-establishes a balance at a system frequency other than the nominal frequency of 50 Hz and, in doing so, also causes power interchanges between individual control areas to deviate from the agreed / scheduled values, since all control areas contribute to the primary control reserve. The function of secondary control is to keep / restore the power balance in each control area / block and, consequently, the system frequency to the nominal frequency and the power interchanges with adjacent control areas to their programmed scheduled values. This ensures that the full reserve of the activated primary control will be made available again.

The secondary control reserve has to be activated at the latest 30 seconds after any imbalance and to restore the initial state within 15 minutes at the latest. The size of the secondary control reserve generally depends on the size of typical load variations, schedule changes and generating units. Primary and secondary control reserves have to be available for activation independently. (ENTSO-E, 2011)

- **Tertiary Control**

The tertiary control reserve is activated manually or automatically by the TSOs in case of observed or expected sustained activation of the secondary control reserves. Tertiary control reserve (also called minute reserve) is typically operated in succession or, in case of larger incidents, as a supplement to secondary control reserve. Its function is to free up secondary control reserve and any primary control reserve still in use. Sufficient tertiary control reserve has to be available within each control area. The size of the tertiary control reserve depends on the largest expected loss of power (generation unit, power infeed, DC-link or load) in the control area. (ENTSO-E, 2011)

3.2.2 Examples for the Operation of the Control Power Market

In most liberalized electricity markets, TSOs have to procure their need for primary control, secondary control and tertiary control (minutes) reserve in an open, transparent and non-discriminatory control power market. In Germany, for example, a common internet platform of the TSOs (www.regelleistung.net) is used for the processing of the common tender for control reserves since 2007, where the publication of tenders, the completion of the submission of tenders and information for the bidders about acceptance of their bids and / or refusals are announced. All

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prequalified bidders can apply to the tenders. It's the same in Austria in the control area of Austrian Power Grid (APG, TSO) (see www.regelleistung.at).

At the end of each bidding period[11] the bids for primary control reserve are ranked in a merit order according to prices – starting with the cheapest bids – until the total volume of required control power is reached (e.g. 71 MW in Austria, 567 MW in Germany). These bids are accepted, whereby acceptance of the last and most expensive bid may be restricted to ensure that the tender quantity is not exceeded[12].

Figure 8 shows an example for the activated primary control power in the control area of APG on the 22nd of February 2012.

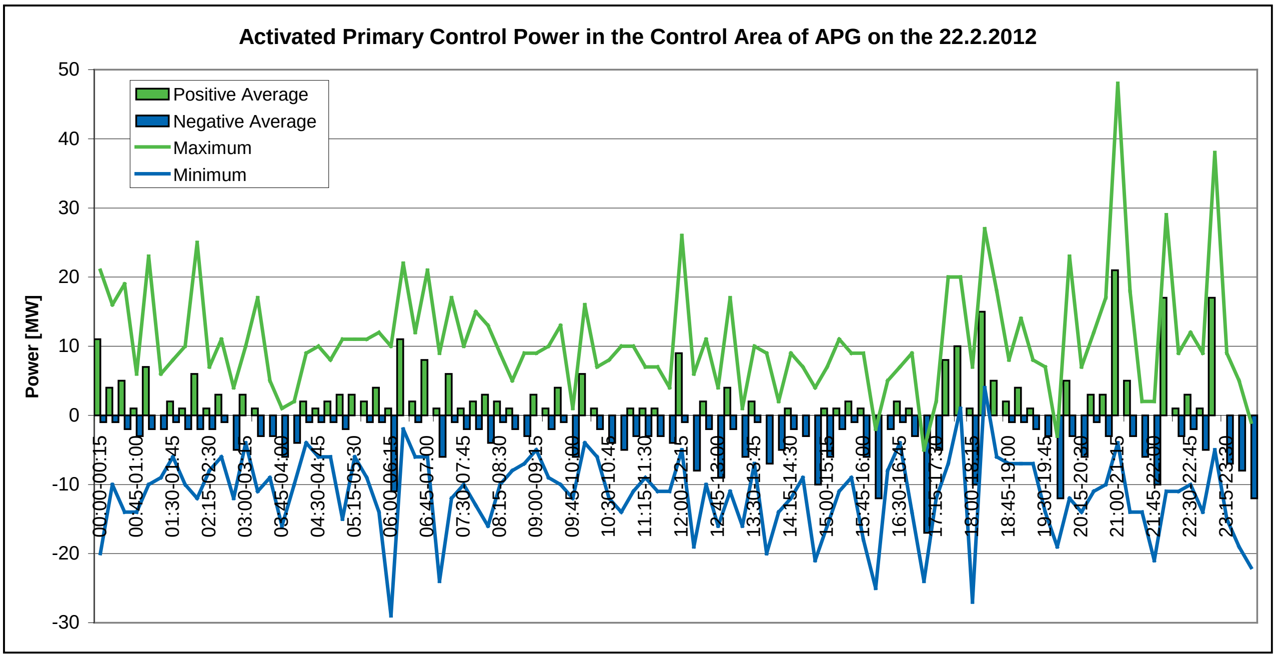

Figure 8: Activated primary control power in the control area of APG on the 22nd of February 2012 (Source: APG, 2012)

In Germany and Austria also secondary control reserve is procured based on a weekly tender. Each TSO is responsible for the provision of secondary control reserve in its own control area. Unlike primary control, separate tenders are run for positive and negative secondary control[13]. Each bid in the secondary control power market consists of two components: the price for control power, on the one hand, and the price for energy delivered, on the other hand. When secondary control power is needed, suppliers also receive an energy price for the delivered secondary control reserve energy in addition to the quoted power price.

Figure 9 shows an example for the activated secondary control power in the control area of APG on the 22nd of February 2012.

[11] E.g. primary control reserve is tendered weekly in Austria and Germany.

[12] Suppliers whose offers are accepted receive the capacity price they quoted, i.e. a "pay as bid" approach is adopted. There is no energy price, i.e. the supplier is not paid for the primary control energy being delivered and the supplier does not have to pay for the primary control energy received (APG, 2012).

[13] E.g. Austrian Power Grid (APG, TSO) control area: +/-200 MW; all control areas in Germany: +2084 MW / -2114 MW in 2012.

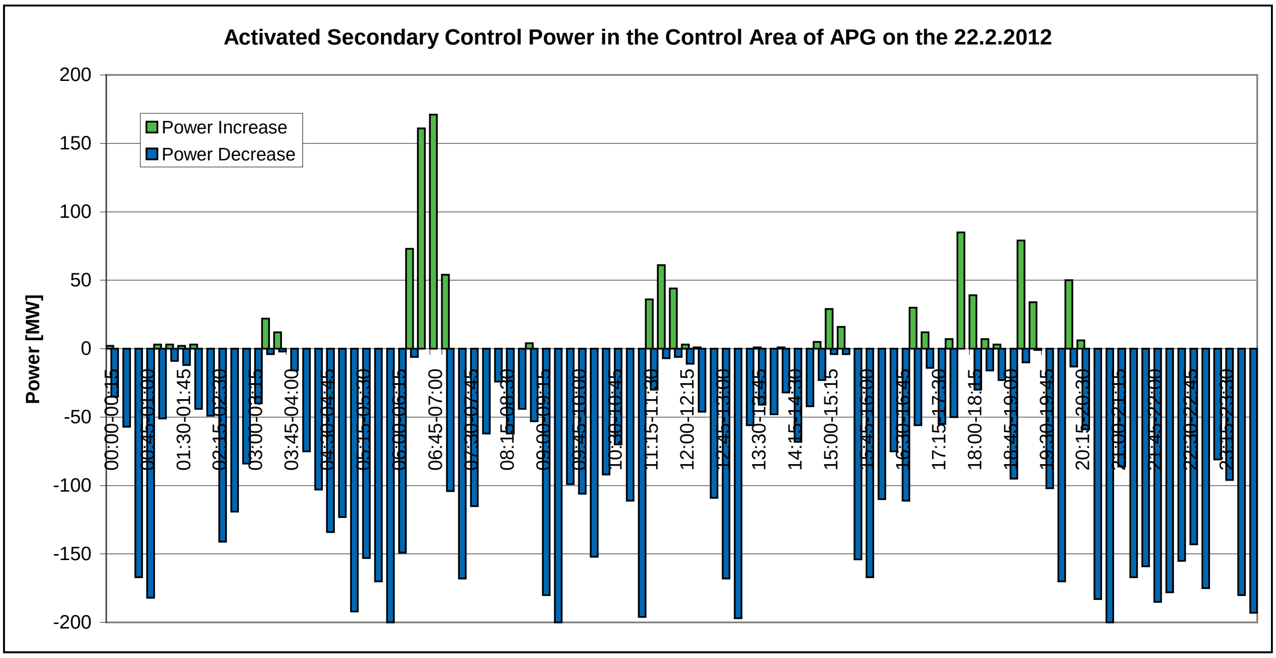

Figure 9: Activated secondary control power in the control area of APG on the 22nd of February 2012 (Source: APG, 2012)

In Germany, tertiary control reserve tenders take place daily on working days for the next working day or the following weekend / public holiday. While the selection of bids is based on the power price demanded by the bidder, the actual activation of the tertiary control reserve occurs on the basis of the energy prices also specified by the bidder in its bids (in a common merit-order list).

In Austria two different tenders exist for tertiary control reserves: one is carried out for the coming weekend (Saturday and Sunday) as well as for the following week (Monday to Friday). The other one is a short-term day-ahead tender where no power price is paid for the reserved tertiary power control. Both tenders have 6 different product time slots. (APG, 2012)

However, in some countries TSOs also procure their need for control reserves via bilateral contracts (e.g. RTE in France).

3.2.3 Applicability and Importance for Bulk EST

Since primary control reserve has to be capable of being activated within seconds, usually bulk EST (PHES & CAES) cannot be applied. However, some special PHES systems exist, like the Dinorwig PHES in the UK, which can set the turbine units spinning in air when the generators are on standby. This way it is able to provide power in around 12 seconds and, therefore, is also applicable for primary control reserve. (Edison Mission Energy, 1999)

The provision of secondary and tertiary control reserves, on the other hand, is of enormous importance for bulk EST, especially for PHES, being able to provide both types of control power (cf. D2.1 of the stoRE project).

Due to increasing shares of RES-E generation, the prices for control reserves, especially the energy prices for negative tertiary control, have been increasing in recent years. (Ehlers, 2011)

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3.3 Intraday Market

3.3.1 Description of the Intraday Market

Intraday markets are operating between the day-ahead markets (see section 3.4) and the physical gate closure, i.e. the point in time after which schedules submitted to the system operator can no longer be changed. Intraday markets are operated either by power exchanges or other market participants and are used for short-term adjustments in case of e.g. power plant outages, load and / or wind forecast deviations. There would be no need for any form of short-term adjustments in case of no changes between the day-ahead planning, trading and real-time operation. The plans would just be realised as scheduled, but this is obviously not the case. Adjustments after the closure of the day-ahead market are needed and may, in principle, be done both through the intraday and the balancing markets. However, in an efficient market design as much as possible of these adjustments would be done in the intraday market to avoid the use of more expensive flexible resources in real-time balancing. (Weber, 2009)

Obviously, there are many different market designs in the different countries, but generally, the intraday markets are continuous markets and trading continuously takes place every day until about one hour before delivery[14]. (Weber, 2009)

Today only very low volumes of total electricity consumed are traded in the intraday markets, but, their importance is expected to increase in the future with higher shares of unpredictable RES-E generation in the electricity system.

3.3.2 Example on the Price Volatility in the Intraday Market

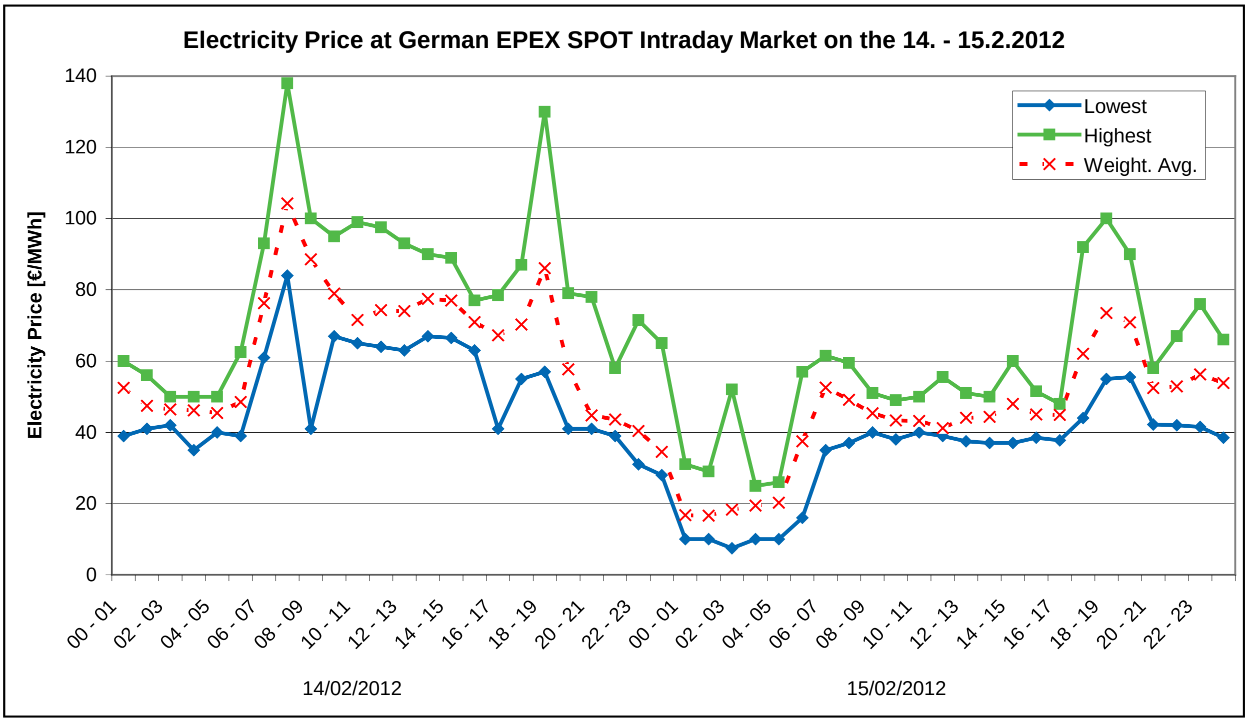

Figure 10: Electricity price at the German EPEX SPOT intraday market on the 14th and 15th of February 2012 (Source: EEG, data: EPEX SPOT, 2012)

[14] E.g. in France and Germany the time frame is 45 minutes before delivery begins (EPEX SPOT, 2012).

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An example on the price volatility in the German intraday market EPEX SPOT is given in Figure 10. It shows the lowest and highest as well as the weighted average of the hourly electricity price on the 14th and 15th of February 2012.

3.3.3 Applicability and Importance for Bulk EST

The intraday market is one of the most important market segments for bulk EST. The electricity price shows high differences between base and peak-load periods (cf. Figure 10) allowing bulk EST to profit from price arbitrage. Also from a technical point of view bulk EST perfectly fit for the short-term adjustments needed in the intraday market.

3.4 Day-ahead Market

3.4.1 Description of the Day-ahead Market

The day-ahead markets are run by power exchanges / system operators are operated on an auction basis. Day-ahead markets (usually labelled “spot market”) are the main markets for the physical delivery of electricity.

At the spot market exchange the hourly price of electricity is determined by matching (forecasted) demand and supply, which is based on supply bids of power plant operators. On perfectly competitive markets these supply bids are based on the short run marginal generation costs (SRMC)[15] without additional (strategic) price components. The market clearing price equals the SRMC of the most expensive generation unit needed to cover electricity demand. (Stoft, 2002)

3.4.2 Example on the Price Volatility in the Day-ahead Market

An example on the price volatility in the German EPEX SPOT day-ahead market is given in Figure 11. It shows the PHELIX[16] Day Base and Day Peak price indices and the corresponding daily base-peak price spreads in 2009.

PHELIX Day Base / Day Peak is the average price of hours 1 to 24 / 9 to 20 for electricity traded on the spot market and is calculated for several calendar days of the year as the simple average of the auction prices for the hours 1 to 24 / 9 to 20 in the market area Germany disregarding power transmission bottlenecks.

3.4.3 Applicability and Importance for Bulk EST

The day-ahead electricity market is an important market for bulk EST since it also offers high base-peak price spreads (cf. Figure 11), being the main source of income for bulk EST operators. However, the short-term markets (e.g. control power and intraday market presented in section 3.2 and 3.3 above) may offer higher revenues than day-ahead markets.

[15] The SRMC mainly consist of the costs for primary fuels (e.g. natural gas, coal etc.) and CO_2 certificates and to a lesser extent of other variable costs (e.g. operation and maintenance cost).

[16] PHELIX refers to the Physical Electricity Index.

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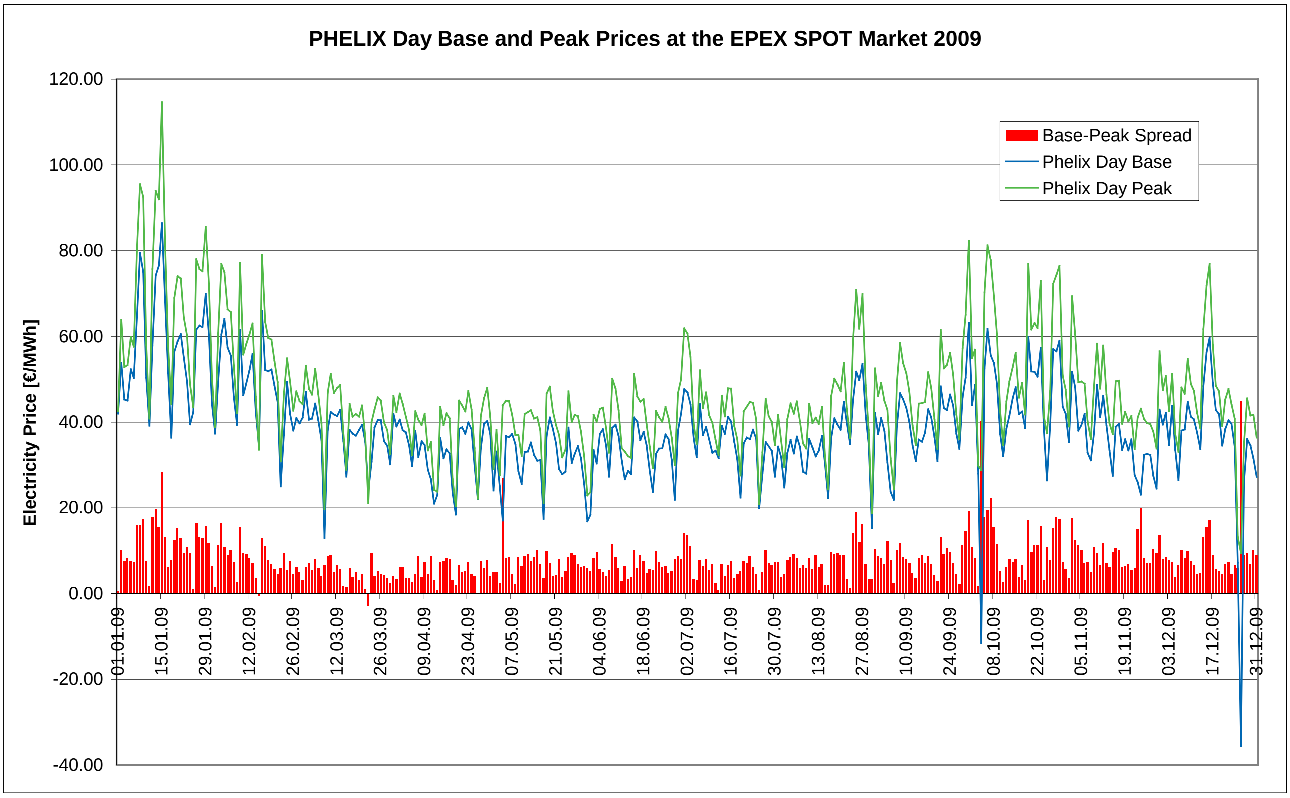

Figure 11: PHELIX day base and peak price indices and base-peak spread at the EPEX SPOT market in 2009 (Source: EEG)

3.5 Forward / Futures Market

3.5.1 Description of the Forward / Futures Market

In forward / futures markets the price formation and delivery are distinct. Delivery can take place up to years after the corresponding prices have been agreed upon the market. Forward / futures markets have two main functions in an economy. On the one hand, they provide and aggregate information about future prices and, on the other hand, allow for hedging price risks. In this way they contribute to market completeness and facilitate risk management and risk transfer. (Redl, 2011)

The forward / futures price reflects the expected development of the market and also includes the aggregated expectations and risk premiums for both electricity buyers and sellers. Therefore, the price includes the expected development of major cost drivers of electricity generation such as fuel prices, ETS prices, etc. (Gatzen, 2008)

Forward and futures contracts most importantly differ in terms of their settlement. Forward contracts yield cash flows (i.e. forward price multiplied by quantity) at the maturity date and are typically settled with physical delivery. Futures contracts in contrast comprise cash flows during the remaining time to maturity according to the change in the market value of the contract (i.e. the price changes of the contract). Futures are typically settled financially and traded at organised exchanges. *Since futures prices converge to the spot price due to arbitrage reasons this*

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continuous settlement causes that e.g. for the purchase of the commodity at maturity the prevailing spot price simply has to be paid. (Redl, 2011)

3.5.2 Example on the Price Volatility in the Forward / Futures Market

As an example for the price volatility in the forward / futures market, Figure 12 shows a comparison of the PHELIX base / peak month future for January 2010 (full lines) and the PHELIX day base / peak price indices in January 2010 (dashed lines, assigned to the upper abscissa "Delivery Date"). It can be seen, that the price spread between base and peak of the futures is much bigger than the price spread achieved in their delivery period (January 2010) in the physical day-ahead market.

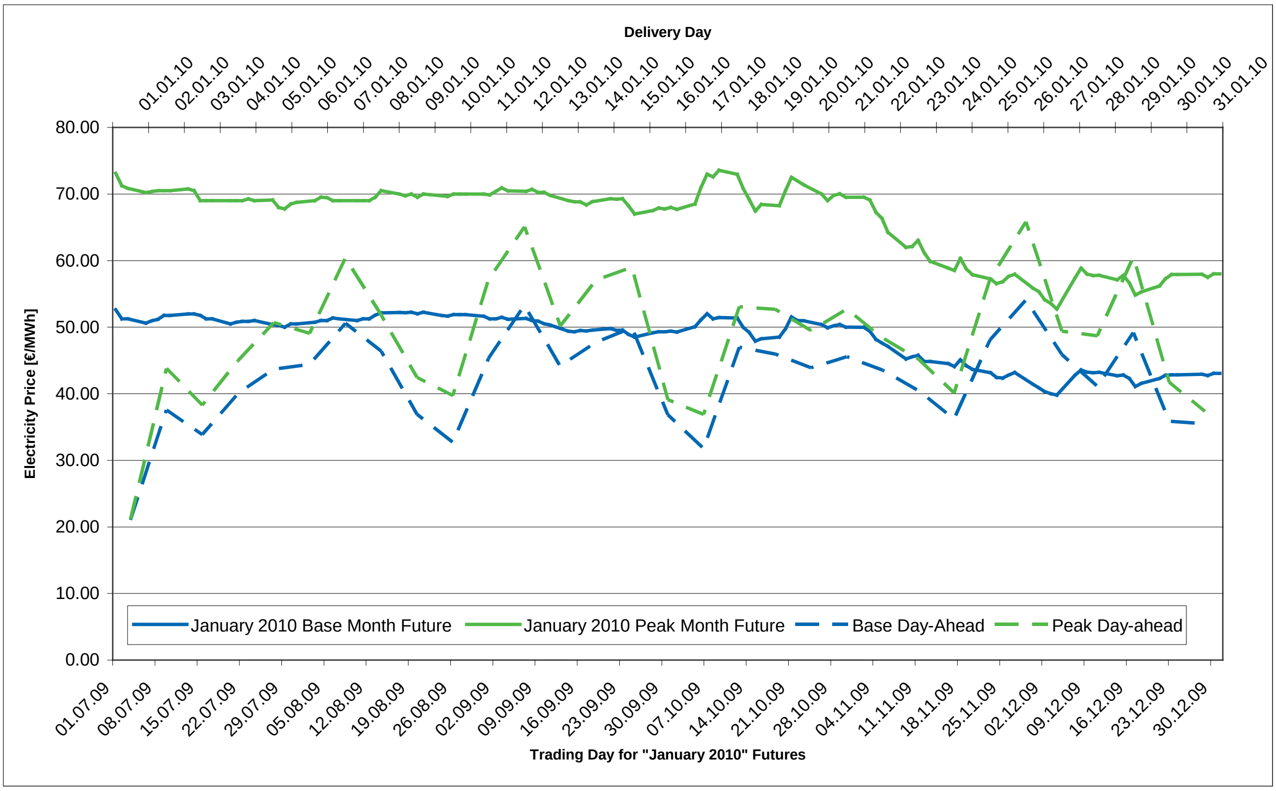

Figure 12: Comparison of the PHELIX base / peak month future for January 2010 and the PHELIX day base / peak price indices in January 2010 (Source: EEG)

3.5.3 Applicability and Importance for Bulk EST

As shown above, also the forward / futures market offers the possibility for price arbitrage. However, these markets need long forward planning and constant deliveries / drawing of electricity over weeks / month / years, which might be difficult to achieve for bulk EST. Therefore, attractiveness of this market segment might be limited for bulk EST in practise.

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4 Limits of Bulk Energy Storage Technologies

4.1 Limits to Storage Capacities of Bulk EST

As already described in section 2 of this report, the integration of non-dispatchable RES-E generation (mainly wind and PV) into the electricity system leads to more frequent fluctuations in electricity supply due to the variable / intermittent character of the used energy source (wind speed and solar irradiance fluctuations). Additionally, PV and most wind power plants are connected through inverters with the electricity grid. This means that they do not serve as additional "rotating mass" in the electricity system. The stored energy in the "rotating mass" of power plant generators (inertia) determines the possible delay of power balancing. (VDE, 2008)

At small penetrations (i.e. a few percent of total installed capacities in the electricity system) the additional balancing effort is likely to be small, since the fluctuations of RES-E feed-in will be small compared to those on the demand side. Higher shares of integrated RES-E generation also mean that the amplitude of power fluctuations will rise in the future. The most challenging situations for system balancing occur when electricity demand and RES-E output are changing simultaneously in opposite directions, e.g. when electricity demand is rising upwards while RES-E feed-in is declining significantly. In these situations the fastest ramp-up and -down times of the flexible power plants in the electricity system providing balancing power are needed. (IEA, 2011a)

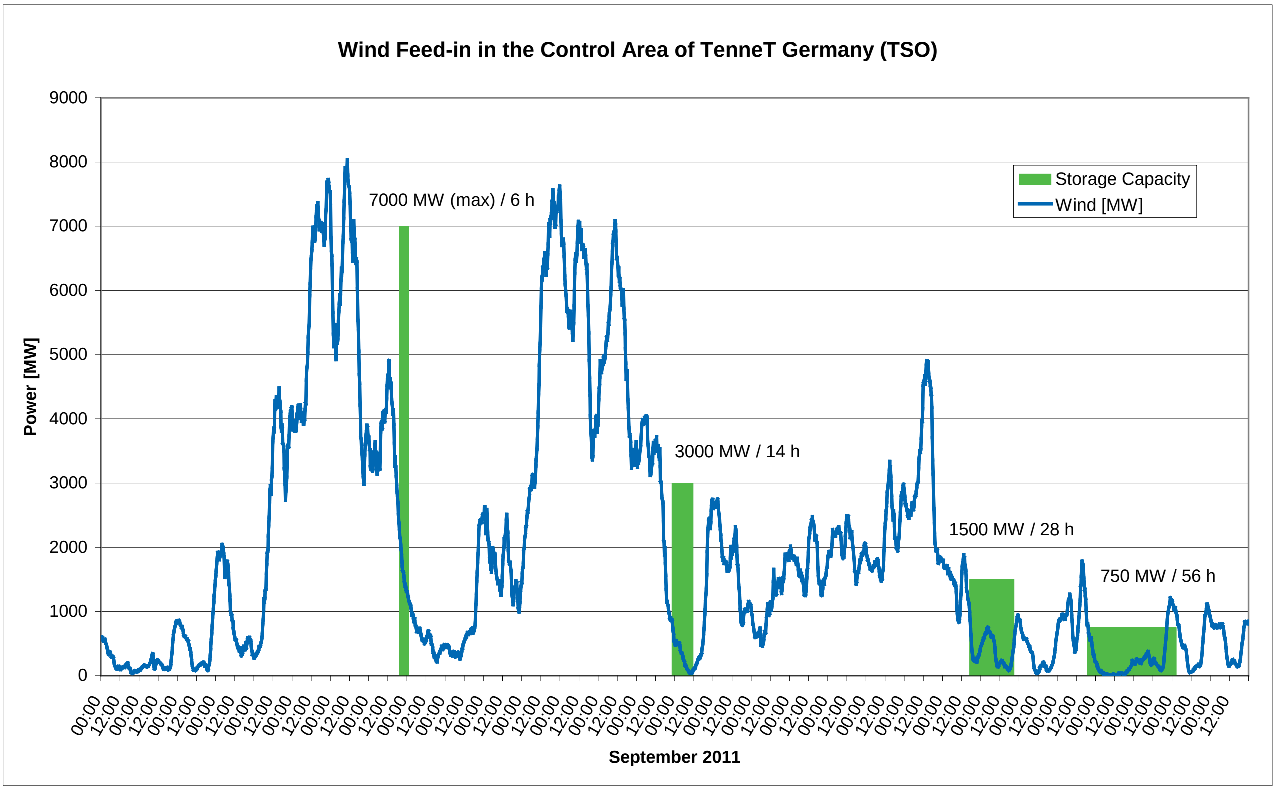

Figure 13: Comparison of the hourly wind power feed-in in the control area of TenneT Germany (TSO) in September 2011 and the available PHES storage capacity in Germany (Source: EEG, data: TenneT, 2011)

Bulk EST (e.g. PHES and CAES systems) have been used for balancing issues for a long time. However, their storage capacities are limited and by no means enough to balance the power fluctuations caused by variable RES-E feed-in exclusively. In this context, Figure 13 shows the hourly wind power feed-in in the control area of TenneT Germany (TSO) in September 2011 and the total available PHES storage capacity in Germany in comparison to each other. The total PHES storage capacity in Germany is about 42 GWh today, depicted in Figure 13 with four different green bars (each with the same area i.e. the same energy amount). It can be clearly seen, that even in the control area of TenneT Germany alone the storage capacities of Germany are not sufficient to balance the fluctuations of wind feed-in.

Especially for longer periods with little RES-E feed-in (e.g. meteorological inversion) and / or times with high RES-E generation fluctuations, additional storage capacities and / or other technology options which increase the flexibility in future energy systems will be needed to balance the future electricity system.

4.2 Other Technology Options to increase Flexibility in future Energy Systems

To mitigate variability in the electricity system confronted with fluctuating demand and RES-E feed-in electricity systems need to be equipped with sufficient flexible resources / flexibility. The flexibility of a power system is described by the capability to maintain reliable supply also in case of rapid and large imbalances, i.e. it can modify generation and / or load in response to variability. The flexibility of a system / power plant can be measured by the power ramp rate up / down in MW/min or %/min.

Higher flexibility can be achieved by adding quickly dispatchable generators to the electricity system, on the one hand, and by accessing other resources like demand side management (DSM), transmission grid extension etc., on the other hand. In the following, the other flexibility options, besides EST, are briefly described.

4.2.1 Dispatchable Power Plants

The ability of dispatchable power plants to ramp their output up / down is the largest source of flexibility in the electricity system. However, not all dispatchable power plants provide the same amount of flexibility. They can, therefore, be categorized into three different groups: base-load, mid-load and peak-load power plants.

Base-load power plants such as run-of-river hydro[17], nuclear, some coal, geothermal etc. are generally designed to operate more or less 8760 h/yr (reduced by maintenance periods). They can provide some flexible response only when notified hours ahead.

Mid-load power plants such as CCGT, some coal and biomass technologies etc. can provide significant flexibility within an hour as they typically have the ability to operate in turndown mode.

Peak-load power plants such as (P)HES, open-cycle gas turbines (OCGT) can respond more or less immediately and, therefore, offer the highest flexibility in the power plant mix. (IEA, 2011a)

[17] Run-of-river hydro power plants are an exception here, since, in principle, they are also highly flexible units, but in case of throttling energy would be lost (bypassing water).

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In Table 2 some typical ramp rates and minimum generation capacity (in % of P_N) of different power plant technologies currently operated in electricity systems are shown in comparison to PHES. It can be clearly seen, that besides PHES and CAES gas turbines and CCGTs only offer high ramp rates and are able to operate at low minimal loads. Nuclear power plants offer good flexibility when operated above 80% of P_N.

Table 2: Ramp rates and minimum generation capacity for different power plant technologies (Source: Hundt et al, 2010)

Technology	Ramp Rate [% of P_N/min]	Min. possible Load [% of P_N]
CCGT	6	33
Coal	3 – 4	40
Gas	20	20
Nuclear	10 4 – 5	80 50 - 60
PHES[18]	> 40	15
CAES[19]	30 – 40	N/A

However, as already described in section 2.2, future economics of conventional electricity generation technologies will suffer from multiple effects accompanied also by a large increase of RES-E deployment.

Also RES-E technologies could provide additional flexibility by curtailing the (variable) output (e.g. for wind, PV etc.), on the one hand, or by adjusting the remuneration rules, on the other hand. Variable RES-E generation could be curtailed to avoid surplus power or even to provide some balancing power when necessary. In case of dispatchable RES-E power plants such as biomass, biogas, etc. additional flexibility can be provided when remuneration rules are adjusted. If dispatchable RES-E power plants receive a fixed payment (e.g. feed-in tariff) they are dispatched regardless of electricity demand. If their payments would be connected with the electricity demand or according to the wholesale market price, dispatchable RES-E could also provide some balancing power. (Gatzen, 2008)

4.2.2 Combined Heat and Power Plants and Heat Storages

The national electricity demand in some European countries (e.g. Denmark or The Netherlands) is already covered by high shares of CHP-based electricity generation. The electricity generation from CHP plants is to some extent driven by the heat demand in the district heating grids connected to the CHP plants. Therefore, these heat-driven CHP plants only contribute to a small extent to the flexibility of the electricity system. (Gatzen, 2008)

However, the amount of heat demand driven electricity generation in CHP plants can be reduced by introducing heat storages, heat pumps and electric heat boilers in connection with the CHP plants. The introduction of heat pumps and electric boilers combined with heat storages is

[18] Source for PHES data: EURELECTRIC, 2011.

[19] Source for CAES data: EPRI, 2011.

beneficial for the integration of non-dispatchable RES-E generation. The benefits include reduced curtailment of non-dispatchable RES-E generation, reduced price of regulating power and reduced hours with very low power prices making non-dispatchable RES-E generation more valuable. The electricity system benefits from heat pumps and electric boilers since they are replacing heat production of fuel oil heat boilers and CHP plants using various fuels. (Meibom et al, 2007)

Also the results of Kiviluoma et al. (2010) show that there is great potential for additional power system flexibility in the production and use of heat.

An example of this increased flexibility from CHP plant is given in Figure 14, where the production from the CHP plant in Skagen (Denmark) on the 25th of March 2011 is shown. The Skagen CHP plant has three 4,7 MW engines, a 11 MW electrical boiler and a 4.000 m^3 thermal storage. On the 25th of March 2011 the Skagen CHP plant won deliveries at three different electricity markets.

In the first four hours it won negative primary control on the 10 MW electrical boiler (orange area). A little before 3 o'clock it won a downward regulation in the regulating power market but still performed the frequency regulation. After 4 o'clock it had not won any more primary reserve - thus offering 10 MW downward regulation in the regulating power market winning it for a full hour. The CHP units were only partly sold in the spot markets from 16 - 20 o'clock, making it possible to offer positive primary control reserve in these four hours.

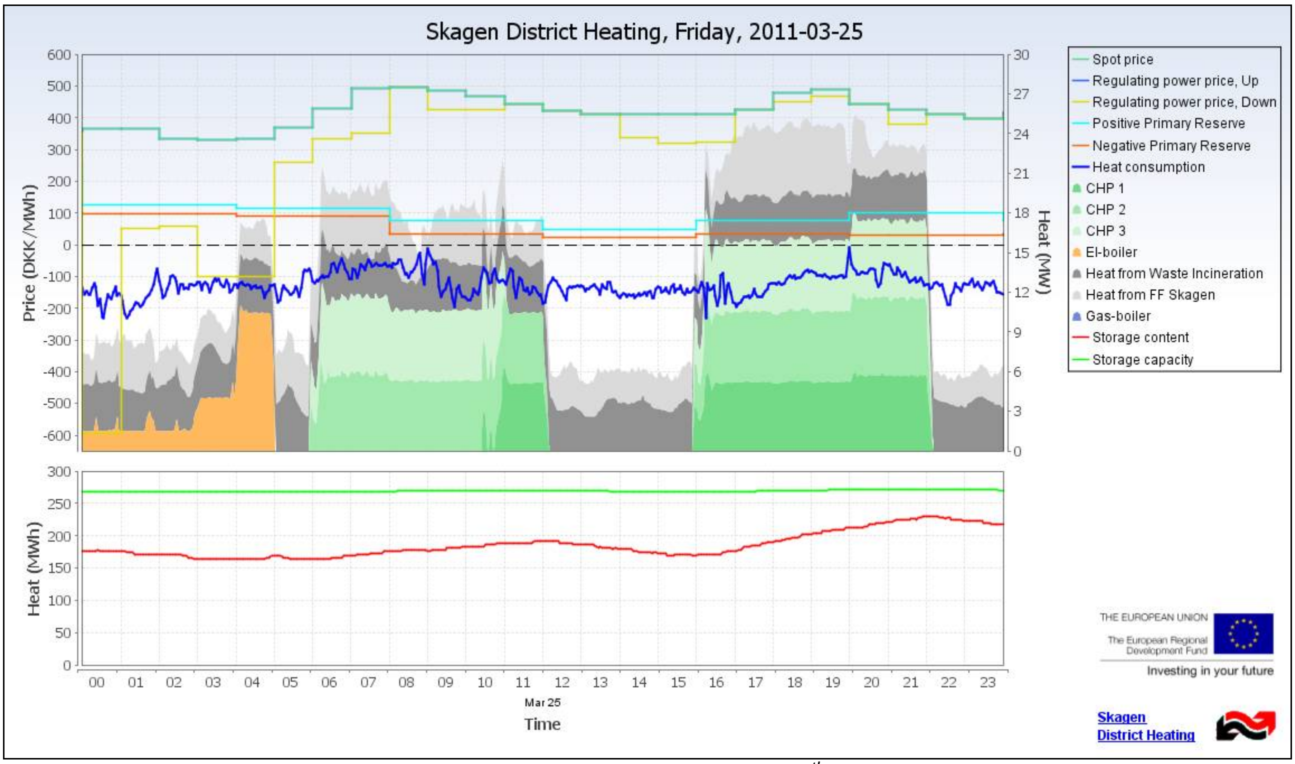

Figure 14: Production of the Skagen CHP plant (Denmark) on the 25th of March 2011 (Source: EMD, 2012)

4.2.3 Demand Side Management

Demand side management (DSM) is the flexible resource on the demand side by fast modification / shift of electricity consumption, i.e. load shifting or curtailing.

Currently, most implementations are installed over small geographical areas only and with limited demand controllability actually offered only. However, the development of advanced information and communication technology (ICT), e.g. smart electricity meters linked to control centres, may offer greater flexibility potential of demand. Especially the flexibility of domestic demand based on pricing electricity differently at different times (e.g. higher prices during higher load periods) may give consumers an incentive to modify and / or reduce their electricity demand. Additionally, all forms of DSM require consumer engagement, in terms of changes in behavioural patterns, social acceptance and privacy / security issues. (IPCC, 2011)

Besides lowering average and peak electricity demand, DSM has also the potential to ease problems of the electricity system with increased variable RES-E generation:

- Mitigation of low capacity credit of some variable RES-E generation during peak load times through reduced demand
- Mitigation of day-ahead forecast errors of variable RES-E generation through participation of flexible demand in intraday balancing
- Mitigation of operational challenges of thermal power plants concerning minimum generation constraints and ramp rates limits
- Provision of frequency regulation, etc. (IPCC, 2011)

The full potential of DSM flexibility resource currently is unknown and more research is needed. However, the key to unlock the potential *will depend on the extent of the incentive to respond, and the ease with which it is possible to do so – effort, as well as economic incentive*. (IEA, 2011a)

4.2.4 Transmission Grid Extension

The power transmission system is the backbone of the electricity system and plays a key role in electricity supply to final customers. The provision of flexibility for an electricity system does not necessarily have to be covered inside the footprint of a single country / market region. Transmission grid expansion can bring synergies into neighbouring electricity systems; besides others (e.g. market coupling, security of supply) transmission expansion can significantly contribute to connect centres of large-scale variable RES-Electricity generation with centres of flexible power generation in a European context. This way transmission grid extension can directly mitigate the impact of variable RES-E generation.

Further on, the operation of the electricity system as part of a larger balancing area or sharing balancing requirements across neighbouring systems reduces the integration costs associated with RES-E generation and also the technical / operational challenges. Additionally, this widening of the balancing area offers the opportunity to reduce net variability and uncertainty of RES-E generation through exploiting greater geographical diversity and a wider range of different RES- E sources. (IPCC, 2011)

The following maps in Figure 15 try to give an indicative overview of the expected increase of cross-border transmission capacities in Europe until 2015 / 2020. Although simplified the maps illustrate that cross-border transfer capability is scheduled to improve on almost all borders in Europe. (ENTSO-E, 2010)

In this context, Figure 16 shows for the German case the simulated power plant dispatch to meet residual load of Germany (wind and PV generation excluded) in January 2020 with currently

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existing (including those under construction) thermal power plants. With the currently existing thermal power plant mix, German PHES potentials alone are not sufficient to balance the increasing fluctuations of RES-E generation in 2020. In case of sufficient cross-border transmission capacities imports from Austrian PHES generation are enabled and these can then contribute to the German balancing situation.

However, building of new transmission lines (especially overhead lines) is generally associated with the problem of low social acceptance. Furthermore, additional incentives for transmission investments may be needed.

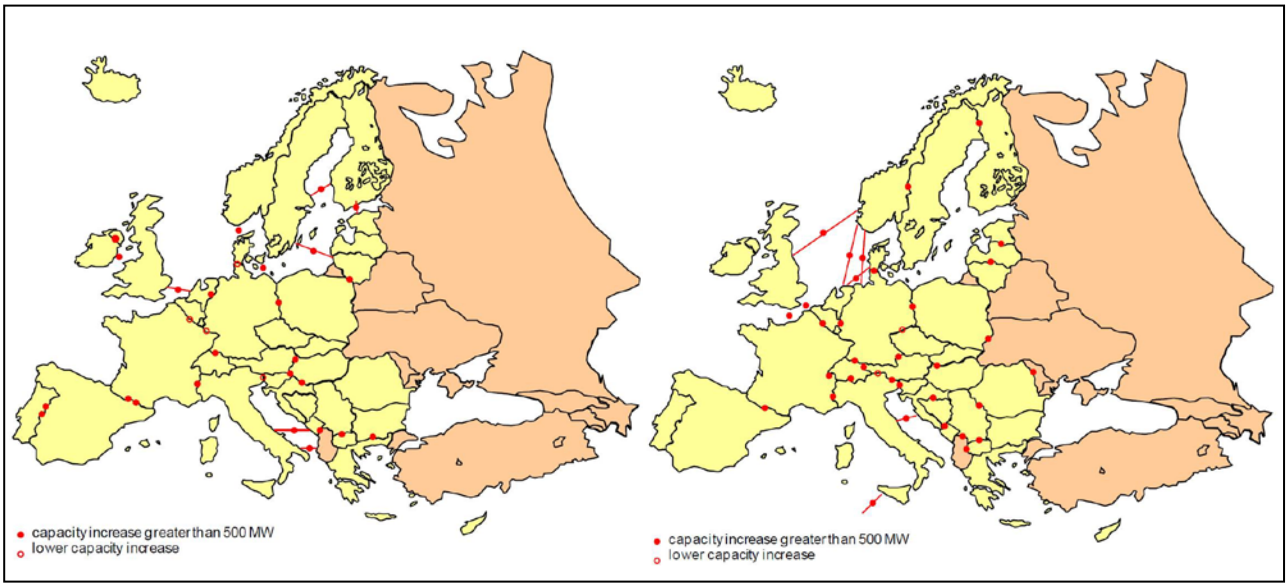

Figure 15: Expected increase in cross-border transmission capacities until 2015 (left) and 2020 (right) in Europe (Source: ENTSO-E, 2010)

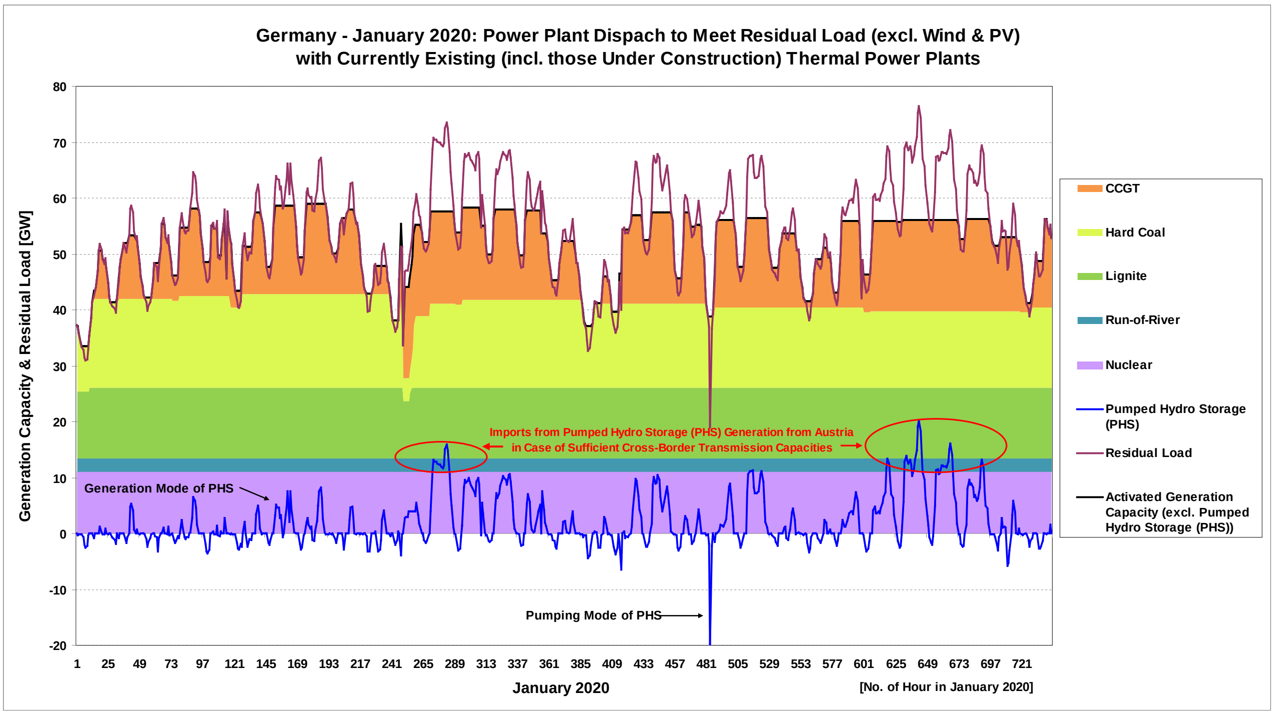

Figure 16: Power plant dispatch to meet German residual load (wind and PV generation excluded) in January 2020 with currently existing thermal power plant mix (Source: Juranitsch, 2011)

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5 Conclusions / Outlook

This report provides an overview on the requirements / challenges of bulk EST in future energy systems with high penetration of RES-E generation.

At first, possible future challenges of bulk EST due to high shares of variable RES-E generation are summarized. Some RES-E technologies, e.g. bio-energy, geothermal, etc. are dispatchable and, therefore, can be easily integrated into the electricity system. However, the ongoing integration of large amounts of non-dispatchable wind and solar power into the European electricity system induces more frequent and uncertain price fluctuations on the competitive spot market due to changing feed-in. This additional volatility in electricity generation also increases demand for control reserves and also leads to higher balancing demand for conventional power plants. However, due to increasing part-loaded operation (lower efficiency, higher O&M costs) and decreasing full-load hours, conventional thermal power plants will increasingly become less economical.

Since bulk EST rely on volatility of electricity prices and are also able to provide control reserves, the increasing deployment of non-dispatchable RES-E generation technologies also favours the deployment of bulk EST. Though increasing RES-E generation might also have a negative economic effect for bulk EST, as the merit order effect has the potential to lower arbitrage between peak and off-peak prices in the long-term. Also ETS may lead to a similar effect.

In the second part of the report, the requirements / needs and opportunities of bulk EST in the different market segments of the electricity market on different time scales are summarized. Additionally, examples on the price volatility and on the operation of the different electricity market segments were given. Besides the primary control market, where very fast response times are needed, generally bulk EST can be applied in all described electricity market segments. However, with their potential to generate large amounts of electricity within short time periods, bulk EST fit especially well for the short-term markets, e.g. secondary and tertiary control and intraday markets, offering excellent opportunities for price arbitrage.

The third part of the report provides an overview of other technology options qualified to increase flexibility of future electricity systems, since the (potential) storage capacities of bulk EST are limited and not enough to balance the fluctuations caused by variable / intermittent RES-E feed-in. These technology options include dispatchable conventional thermal power plants, suffering from multiple effects already described before, and additional flexibility from dispatchable RES-E technologies and CHP plants. DSM also has the potential to ease problems of the electricity system with increased variable RES-E generation, which will depend on consumer engagement as well as economic incentives. Transmission grid extensions offer the opportunity of widening the balancing area, i.e. flexibility provision for an electricity system has not necessarily to be covered inside the footprint of a single country / market region. Through exploitation of greater geographical diversity and a wider range of different RES-E generation sources flexibility in an electricity system can be increased in general.

Finally, the possible contribution of extended future transmission corridors and also direct benefits of bulk EST implementation in electricity systems with high variable / intermittent RES-E generation is analysed and discussed in detail in Deliverable 2.3 (D2.3) of the stoRE project.

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