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CONTRIBUTION OF BULK ENERGY STORAGE AND TRANSMISSION INTERCONNECTORS TO MITIGATE VARIABILITY CAUSED BY LARGE-SCALE RES-ELECTRICITY GENERATION IN FUTURE ENERGY SYSTEMS

Karl Anton ZACH, Vienna University of Technology – Energy Economics Group,
Gusshausstr. 25-29/E370-3, 1040 Vienna, Austria
Tel.: +43 1 58801 370366, zach@eeg.tuwien.ac.at
Hans AUER, Vienna University of Technology – Energy Economics Group,
Gusshausstr. 25-29/E370-3, 1040 Vienna, Austria
Tel.: +43 1 58801 370357, auer@eeg.tuwien.ac.at

Abstract

This paper provides an overview on the possible contribution of bulk energy storage technologies (EST) in future European electricity systems facilitating large-scale expansion of renewable electricity generation (RES-E). Initially, the geographic allocation of future potentials of bulk EST and future large-scale wind deployment in Europe are identified (based on the most relevant existing work, studies and modelling results). The identified bulk EST potentials are matched with the spatial dispersion of future RES-E deployment and the existing thermal power plant-portfolio on region-level in Europe. A methodology for the derivation of the residual load curves of the different European electricity regions and their possible coverage with existing thermal power plants and bulk EST is presented. Selected results for the years 2030 and 2050 for two different RES-E deployment scenarios are also shown. Furthermore, the contribution of transmission interconnectors for bringing together variable RES-E generation and bulk EST in different European regions are discussed both quantitatively and qualitatively. In general, it can be observed that existing and new pumped hydro energy storage systems (PHES) (and additional flexible thermal power plant units) are strongly needed in almost all of the European electricity market regions to (partly) cover the future electricity generation gap.

1. Introduction

The significantly increasing deployment of variable renewable electricity generation (RES-E) like wind (onshore, offshore) and solar photovoltaic (PV) is changing the way electricity systems have to be operated and managed in the future. Due to the high shares of variable RES-E generation (mainly wind) future electricity systems will be increasingly "stressed" on several scales in time in both dimensions "amplitude" and "frequency". Therefore, proper technologies have to be implemented bringing necessary flexibility into future electricity systems. In general, the two most promising candidates in this context are:

(i) bulk energy storage technologies (EST) like pumped hydro energy storage (PHES) and / or compressed air energy storage (CAES) and

(ii) transmission capacity expansion providing access to flexible electricity generation technologies.

The ability of bulk energy storage technologies to quickly discharge large amounts of stored electricity or to reduce loads during certain points in time throughout a day (e.g. providing regulating power, output smoothing, etc.) can mitigate many challenges which arise with high shares of variable RES-Electricity generation in the electricity system. On the one hand, additional variable RES-Electricity introduces more frequent price fluctuations in the energy system, on the other hand, lowers the price arbitrage between peak and off-peak periods which is an essential parameter for the determination of the economics of energy storage.

The provision of flexible generation capacity for an electricity system has not necessarily 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-E generation with centres of flexible power generation in a European context.

This paper analyses the provision of flexible generation capacity for future electricity systems by bulk EST as well as transmission grid expansion based on selected European case studies.

2. Methods

2.1 Geographical Allocation of Future Potentials for Bulk Energy Storage Technologies and Future Large-scale Wind Deployment in Europe

First, the geographical allocation of future potentials of bulk EST and future large-scale wind deployment across Europe is identified. The estimation of the future potential of bulk EST implementation is based on a summary and synthesis of the most relevant existing work, studies and modelling results on this topic (on country level as well as on European level: [2], [3], [4], [5] and [6]). Due to lack of data sources on future deployment and potentials of CAES systems (currently only one operating CAES power plant and one under development in Germany), future potentials of (pumped) hydro energy storage ((P)HES) systems in Europe were considered in the analysis only.

Figure 1 shows that the highest total potentials for (P)HES are located in parts of Scandinavia, Central and Western Europe. Besides Norway and Sweden, European countries in mountainous areas, such as the Alps and the Pyrenees, have significant potential for deployment of PHES systems. Particularly Luxembourg, Switzerland and Austria have a very high PHES potential in relation to their land area. Otherwise, countries with a rather flat landscape like Denmark, Finland, Latvia and the Netherlands have no existing (P)HES power plants and also no development plans for new PHES systems at the moment[1].

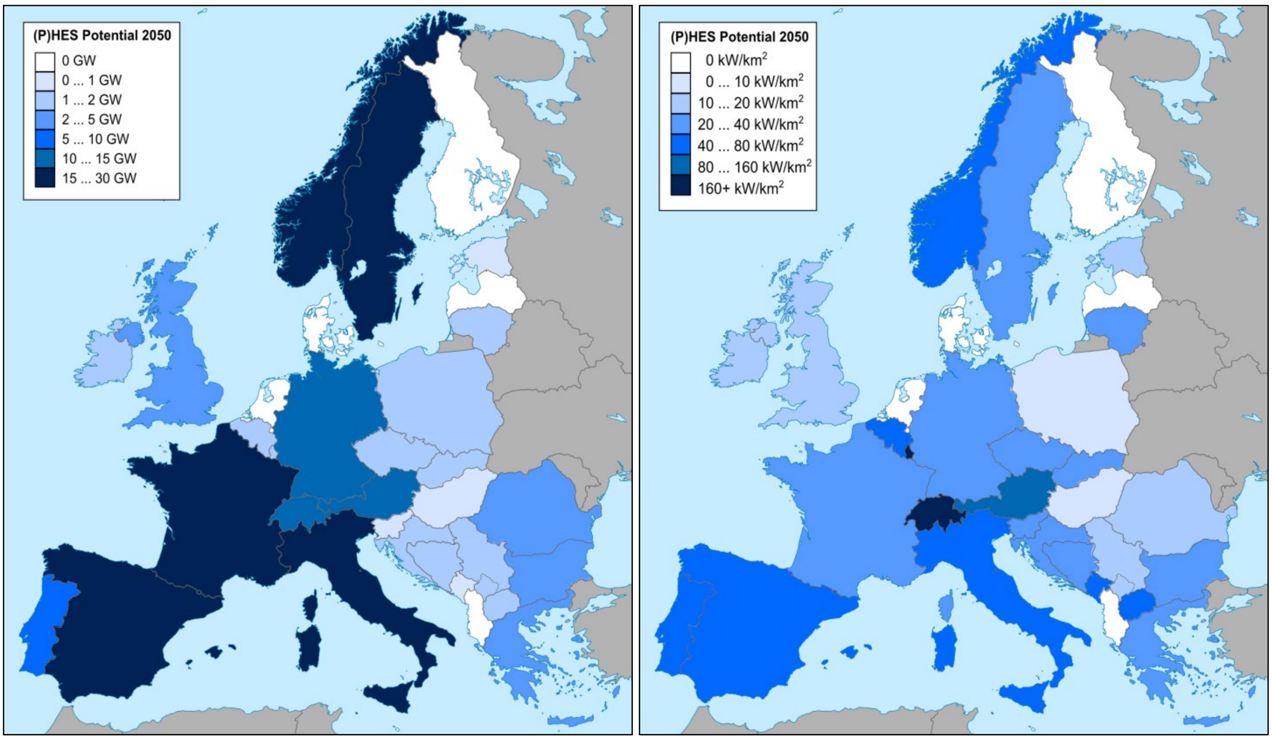

Figure 1: (P)HES potential in Europe until the year 2050: Power capacity per country [GW] (left) and power capacity per land area per country [kW/km²] (right) (Data source: see text above)[2]

For the analyses, two different future RES-E deployment scenarios in European countries for the years 2030 and 2050 are generated based on modelling results derived from the Green-X [7] RES-Electricity deployment simulation tool. Green-X provides future scenarios on annual RES-E capacities installations and electricity generation per country under a variety of different possible policy settings and constraints. The two generated scenarios are, one the one hand a business-as-usual scenario (BAU) with moderate increase of RES-E deployment and an environmentally friendly scenario (GREEN) with high increase of RES-E deployment in Europe, on the other hand. The generated wind deployment in European countries in the year 2050 in the GREEN scenario is given in Figure 2. It can be seen that, in absolute terms, especially Germany,

[1] No data is available for Albania.

[2] See [1] for input data tables.

Spain, UK and France are expected to have very high installed wind capacities in the year 2050, whereas most Balkan & Baltic countries show a low future wind deployment in both scenarios only.

Taking into account the physical constraints in the European (cross-border) transmission grid in the analysis, European countries were clustered into nine different electricity market regions according to the different wholesale electricity market places / prices (as a consequence of physical constraints in the transmission grid). This clustering coincides with relevant EC documents [8] and [9] (e.g. EC infrastructure package) and the ENTSO-E's "Ten Year Network Development Plan (TYNDP)" [10] and is shown in Figure 2. Additionally, Figure 2 also presents the regional (P)HES potential and the future wind deployment in the year 2050 in the GREEN scenario, representing the sum of respective installed capacities / potentials in countries included in the region.

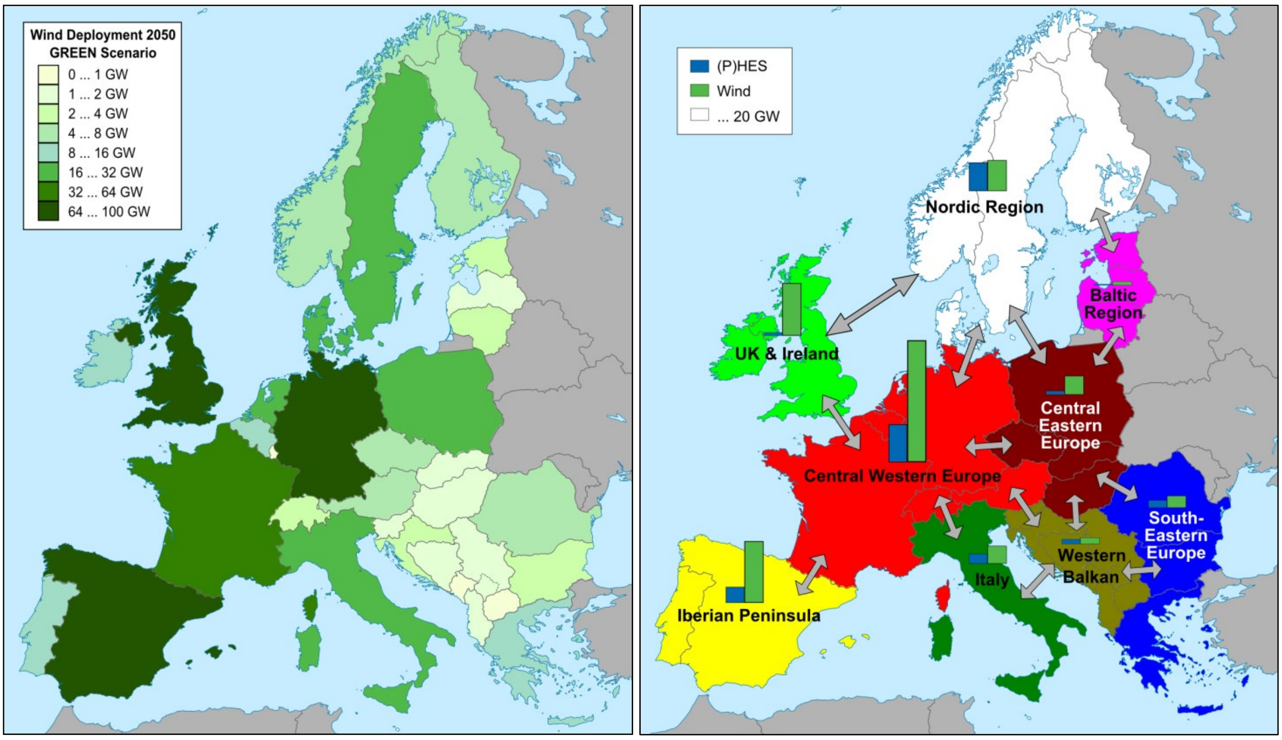

Figure 2: Wind deployment in Europe in the year 2050 in the GREEN scenario (left) and clustering of countries to nine different European electricity regions (right)[2]

2.2 Matching Spatial European Dispersion of Wind Deployment and Bulk Energy Storage Technology Potentials

In order to be able to estimate the possible direct benefits and future contribution of bulk EST implementation to balance an incumbent regional electricity system, the identified bulk EST potentials are matched with the spatial dispersion of future RES-E deployment and the existing thermal power plant-portfolio on region-level in Europe. Doing this, the residual load curves of the nine different regions for the years 2030 and 2050 and for two different scenarios (BAU and GREEN) were derived and its possible coverage with existing thermal power plants and bulk EST was analysed.

For the derivation of the load duration curves and residual load curves in the different European electricity market regions for the years 2030 and 2050, the following input data were used:

- ***Electricity Demand:*** Electricity demand data on hourly basis and on country level was taken from ENTSO-E for the year 2010 [11][3]. Table 1 shows the different growth rates of electricity demand used in the BAU and the GREEN scenario for the different time periods. Additionally, the growth rates were differentiated between Eastern and Western Europe[4]. The ENTSO-E electricity demand data is including the network losses but excluding consumption for PHES (pumping mode) and consumption of

[3] No data was available for Albania (therefore not included in the analysis).
[4] Eastern Europe: Central Eastern Europe, Western Balkan, Baltic region, South Eastern Europe without Greece.

generation auxiliaries. With this data the regional load duration curves were established for the years 2030 and 2050 (cf. Figure 4).

Table 1: Growth rates for electricity demand in the BAU and GREEN scenario for different time periods

	BAU Scenario		GREEN Scenario	
Time Period	Western Europe	Eastern Europe	Western Europe	Eastern Europe
2010 – 2030	1.90%	2.50%	0.95%	1.55%
2030 – 2040	1.30%	1.90%	0.60%	1.20%
2040 – 2050	1.00%	1.60%	0.30%	0.90%

- ***RES-E Deployment until 2050:*** Annual deployment of RES-E technologies on country-level until 2050 was generated based on modelling results derived from the Green-X [7] RES-E deployment simulation tool. The RES-E share of total electricity demand in all nine electricity market regions for the two different scenarios is shown in Figure 3. Since hourly data is needed for the establishment of the residual load curves of each electricity market region, additional working steps had to be carried out.

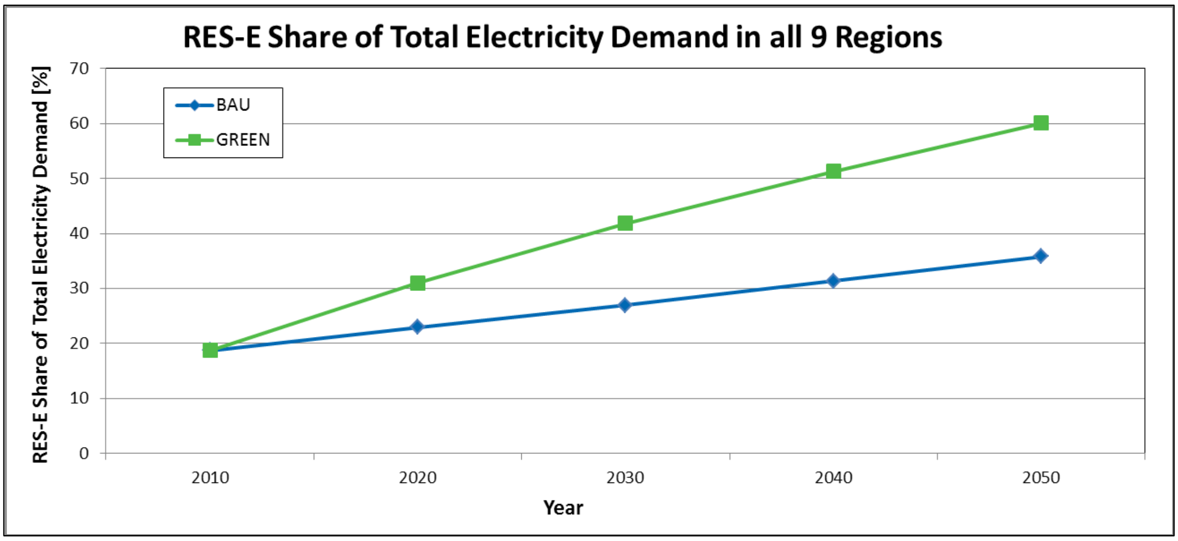

Figure 3: RES-E share of total electricity demand in all nine electricity market regions

- ***Hourly PV Electricity Generation:*** To establish hourly PV electricity generation within each region, hourly global solar radiation data were used from SoDa [12]. Four different reference locations (Seville, Munich, Copenhagen and London) were selected to generate approximate data sets for hourly solar radiation in the different regions depending on their geographical allocation. They were then multiplied with a conversion factor and installed PV capacities in the respective region (from Green-X) to establish hourly PV electricity generation (cf. Figure 4).
- ***Hourly Wind Electricity Generation:*** To approximate hourly wind electricity generation within the European electricity regions, the German wind electricity generation profile data from the Fraunhofer IWES study [13] was taken as a reference and was used to derive hourly wind data for all regions (cf. Figure 4).
- ***Hourly Electricity Generation of Other Renewables:*** Other RES-E technologies (e.g. biomass, biogas, geothermal, etc.) were approximated as constant generation bands throughout the year (cf. Figure 4).
- ***Hourly Run-of-River Hydro Electricity Generation:*** In order to incorporate seasonal water availability difference between winter and summer, the installed capacities of run-of-river hydropower plants were multiplied with a factor of 0.4 in winter (i.e. 1st of January) and 0.9 in summer (i.e. 1st of July) and linearly scaled in between (cf. Figure 4).

An example for the established set of regional residual load curves is shown in Figure 4, where the load duration and residual load curve for the Central Western Europe (CWE) region in the year 2030 is given. In general, the residual load curves (purple line) were generated by subtracting hourly PV (yellow area), wind (dark blue area), other renewables (green area) and run-of-river hydro (light blue area) electricity generation from the load duration curve (black line). Note, that after every subtraction of respective RES-E feed-in from the load, the residual load curve is sorted again from highest to lowest residual load values. Therefore, a vertical cross-section from the load curve to the residual load curve does not determine RES-E feed-in at a certain point in time simply because it represents RES-E feed-in data from different points in time.

In order to be able to roughly estimate the possible direct benefits of bulk EST implementation and their future contribution to the incumbent electricity system, the existing thermal power plant-portfolio within the different European electricity market regions was also considered. Doing this, the age structure and the phase-out of the existing thermal power plant-portfolio (see Figure 5 for an example) were generated from the PLATTS database [6] for all different electricity market regions. Installations of new thermal power plant capacities up to the year 2015 are already considered within the database.

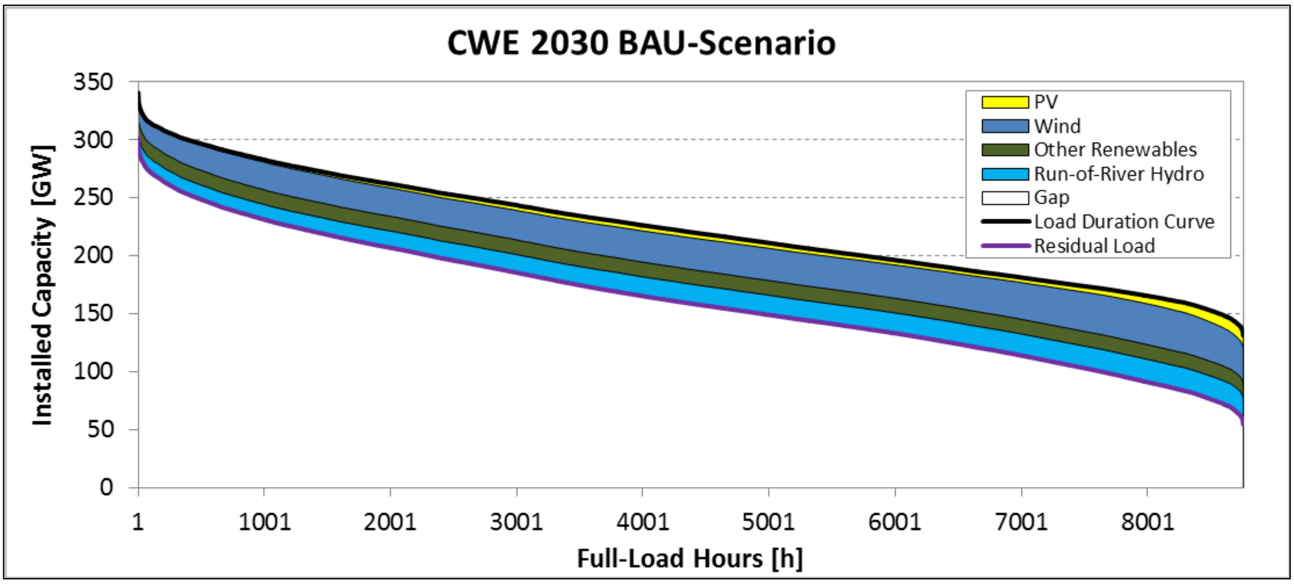

Figure 4: Load duration and residual load curve for the CWE region in the BAU scenario in the year 2030

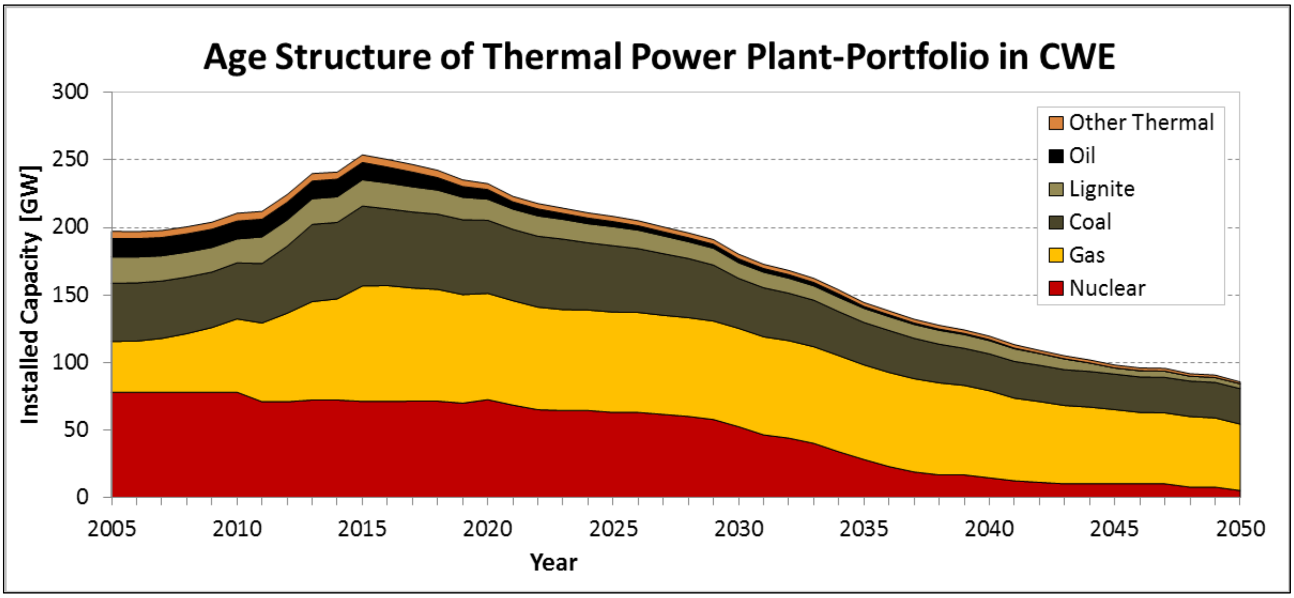

Figure 5: Age structure of the thermal power plant-portfolio in the CWE region (Data source:[6])

After deriving the age structure of the thermal power plant-portfolio in the different regions, established residual load curves for the years 2030 and 2050 were “filled-up” with the still existing thermal power plant capacities (cf. Figure 6). The thermal power plant capacities are drawn as constant bands, starting with the base-load and least-costly power plants (i.e. nuclear, lignite and coal) followed by gas and oil power plant capacities. In order to incorporate power plant availabilities also (i.e. offline periods due to maintenance etc.), installed thermal power plant capacities were multiplied by a factor of 0.8 (nuclear) and 0.9 (all other thermal power plants) respectively.

Additionally, existing installed capacities of PHES systems in the respective region are depicted as constant bands indicated downward from the top of the residual load curves in order to show their potential for providing peak-load power. Any available additional PHES potentials (currently not implemented) within the region are indicated by blue arrows pointing downwards (cf. Figure 6). The electricity consumption of existing and future PHES systems in pumping mode is not incorporated in the residual load curves. However, in general this additional demand would only alter the residual load values in times of high RES-E feed-in / low residual load (i.e. right side of the residual load curve).

In many analysed regions and time horizons a gap (indicated in white colour) remains between the PHES band and the upper band of the thermal power plants, meaning that there is not enough installed power plant capacity available within the region to meet regional electricity demand. For these competitive areas an economic trade-off analysis between the different types of new thermal power plants has to be conducted. The most economic new thermal power plant type is the competitor / benchmark for new PHES power plants.

Figure 6 shows an example of the coverage for the 2030 residual load in the CWE region with existing thermal power plants and PHES systems in the BAU scenario. It can be seen that in the CWE region a capacity gap of about 60 GW remains in the year 2030, meaning that new thermal and / or PHES power plants will be needed to cover electricity demand. The blue arrow indicates that a maximum of about one third of this missing capacity could be provided by new, currently not utilized PHES systems.

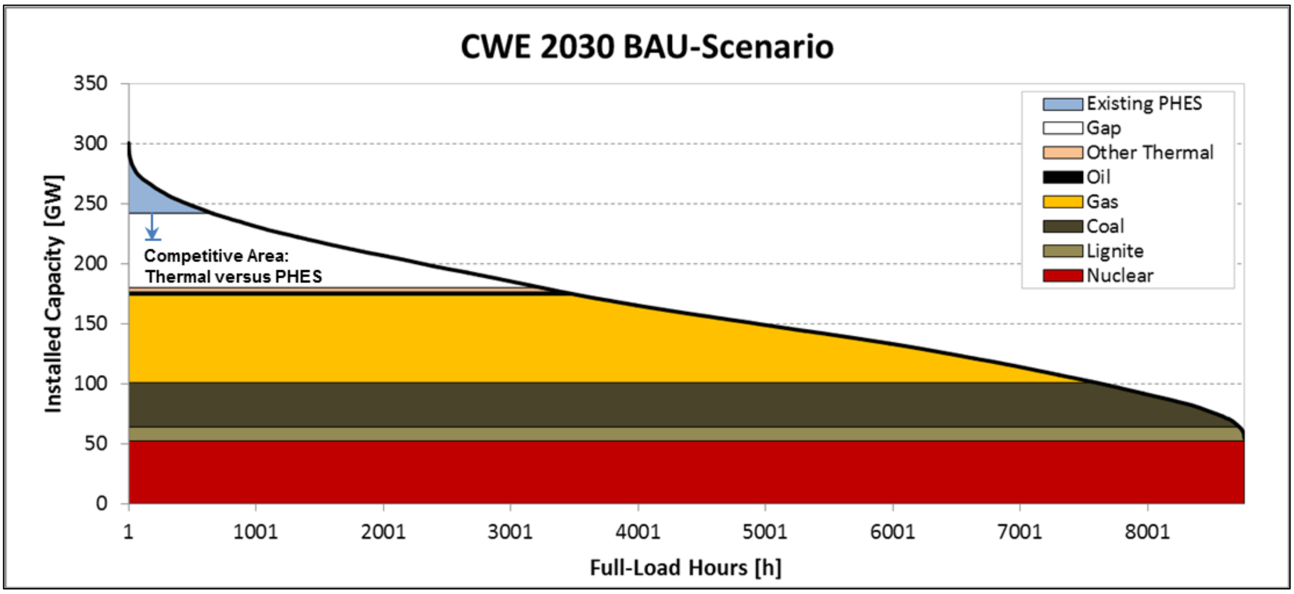

Figure 6: Coverage of the 2030 residual load of the CWE region with existing thermal power plants and PHES in the BAU scenario

3. Results

In the following, results of the BAU and GREEN scenario in the year 2030 and 2050 are shown for the Nordic region, the Iberian Peninsula and the CWE region. The result figures for remaining regions can be found in [1].

3.1 Iberian Peninsula (BAU scenario 2030)

Figure 7 and Figure 8 show the construction of the residual load curve and its coverage with existing thermal power plants and PHES in the BAU scenario for the Iberian Peninsula in the year 2030.

It can be seen that sufficient (thermal) power plant capacity is available in the region (i.e. no capacity gap between supply and demand). This fact has two reasons: On the one hand, high RES-E deployment in the region (especially wind, but also PV) and, on the other hand, large amounts of still existing thermal power plants in the year 2030 (due to high investments in gas-fired thermal power plants in the last ten years in the Iberian Peninsula).

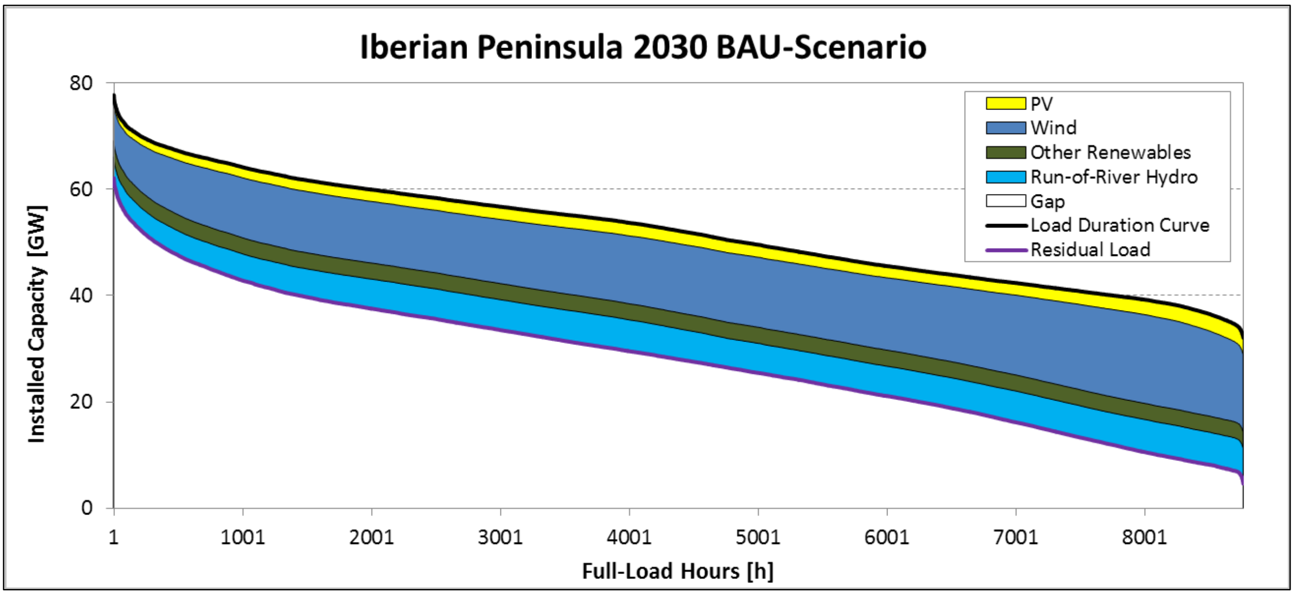

Figure 7: Load duration and residual load curve for the Iberian Peninsula in the BAU scenario in the year 2030

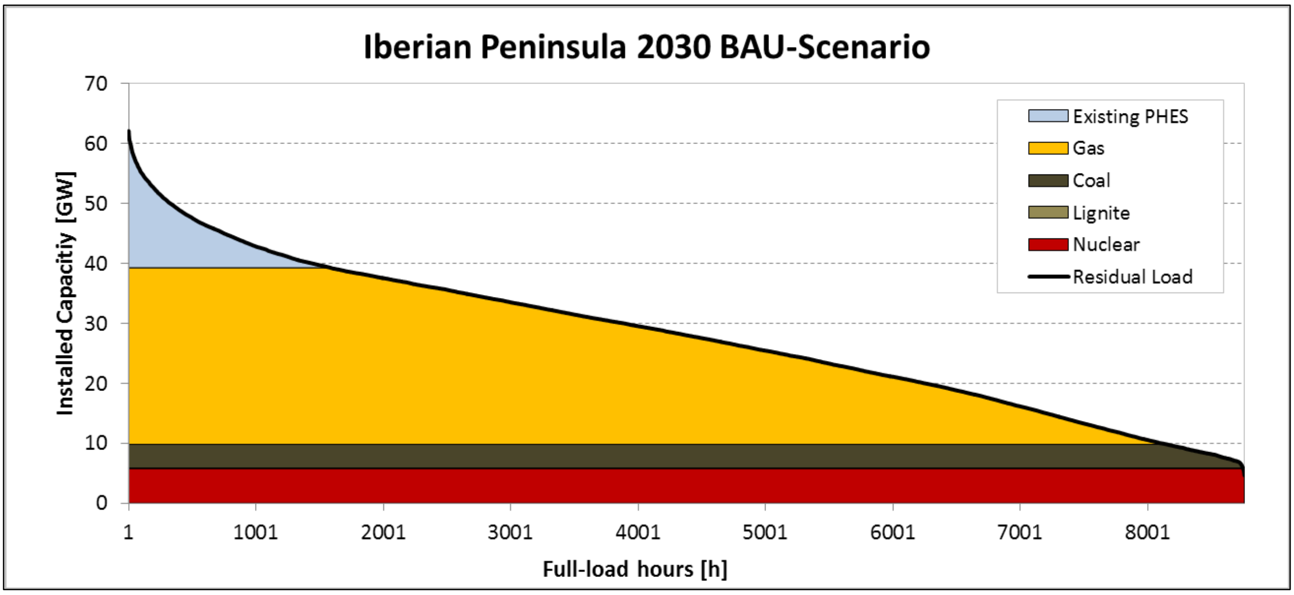

Figure 8: Coverage of the 2030 residual load of the Iberian Peninsula with existing thermal power plants and PHES in the BAU scenario

This set of flexible gas-fired electricity generation technologies (i.e. combined- and open-cycle gas turbines) is perfectly qualified to balance electricity systems and to provide reserve capacities in electricity systems with high shares of variable and intermittent RES-E generation[5]. These gas-fired generation technology types

[5] See [14] for more details.

are needed and, alongside bulk EST systems, they are key candidates for maintaining smooth electricity system operation; especially peripheral areas of electricity systems, i.e. in an European context in the Iberian Peninsula, Italy, the United Kingdom & Ireland (necessity depending also on the future interconnection with the Nordic region) and also other areas, such as the Balkan region (in the future most probably passed through by gas pipelines like "Nabucco" and / or "South Stream"). These countries also have access to natural gas (either own resources and / or transit countries of natural gas corridors / hubs) as a primary energy carrier.

3.2 Nordic Region (BAU scenario 2030)

Figure 9 and Figure 10 show the construction of the residual load curve and its coverage with existing thermal power plants and (P)HES in the BAU scenario for the Nordic region in the year 2030.

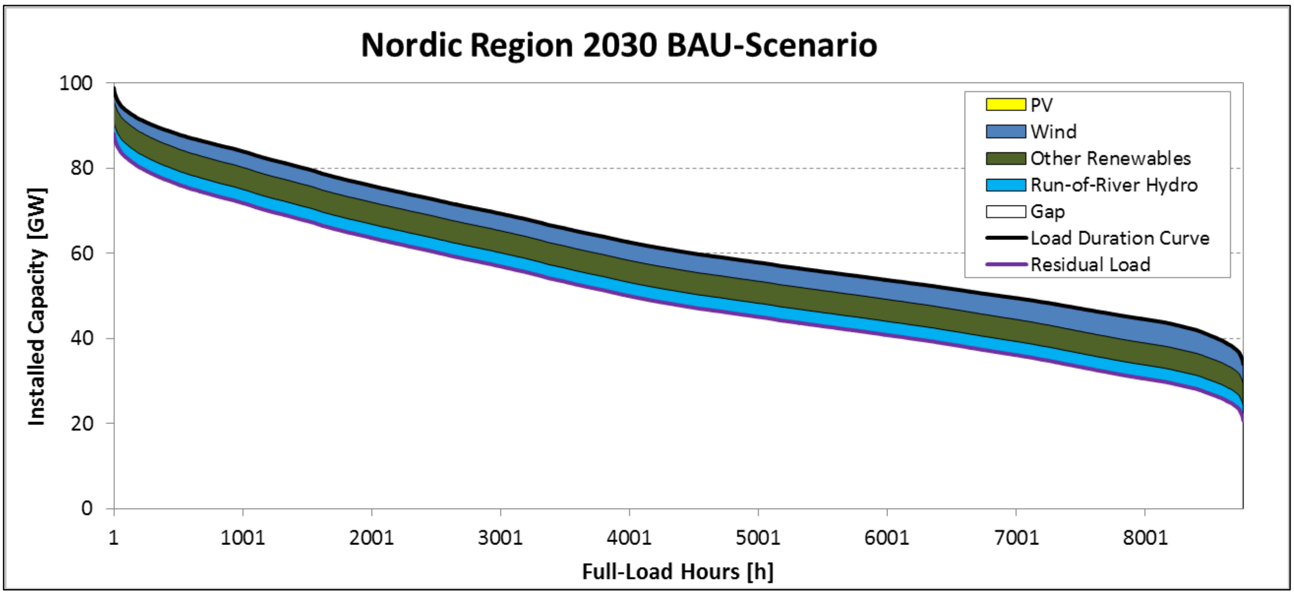

Figure 9: Load duration and residual load curve for the Nordic region in the BAU scenario in the year 2030

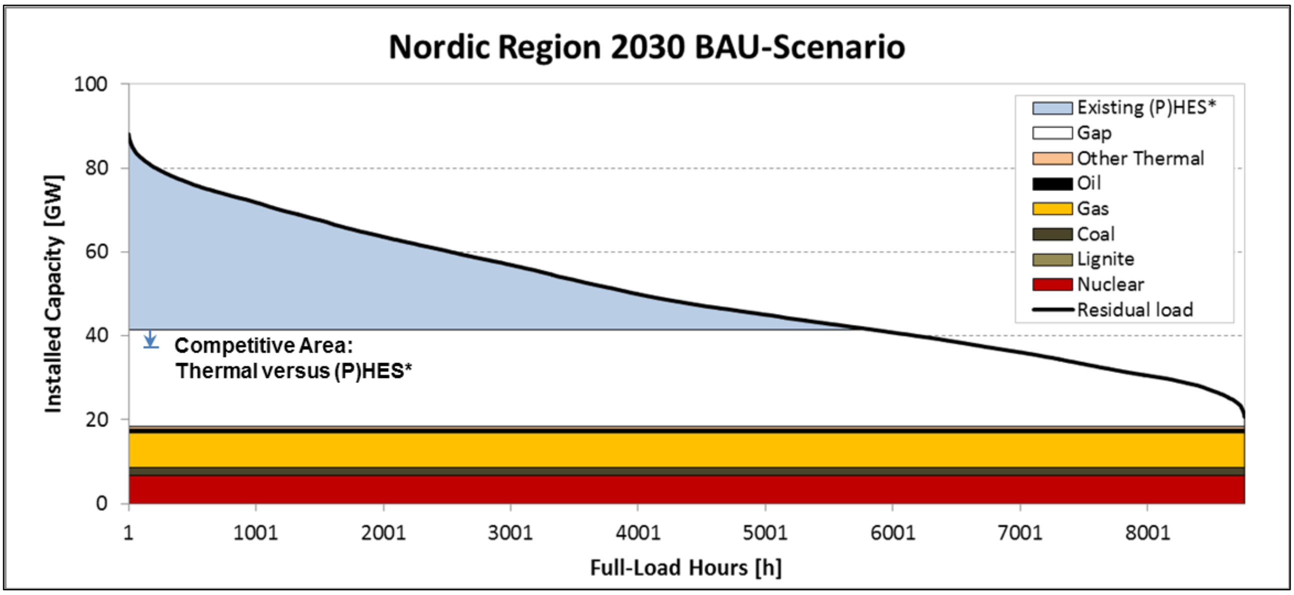

Figure 10: Coverage of the 2030 residual load of the Nordic region with existing thermal power plants and (P)HES in the BAU scenario

The Nordic region is characterized by large amounts of HES systems (especially Norway, but also Sweden) being a highly flexible electricity generation technology. Currently, there are only few PHES systems in the region. However, in order to incorporate also the flexibility of the existing HES systems and the possibility of upgrading them to PHES, the total sum of existing HES and PHES systems is indicated in Figure 10 as existing (P)HES. These existing (P)HES systems are capable to cover major parts of the residual load, but still leave a gap of missing generation capacity in the year 2030, which could partly be filled by new (P)HES schemes.

3.3 Central Western Europe (GREEN scenario 2050)

Also in the CWE region RES-E feed-in exceeds electricity load occasionally in the year 2050 in the GREEN scenario (cf. Figure 11 and Figure 12). However, due to phase-out of the majority of nuclear and lignite power plants in the region, large amounts of integrated RES-E cannot hamper the growth of the gap of missing generation capacity in comparison to the BAU 2030 scenario. However, new PHES schemes could significantly contribute to minimise this gap.

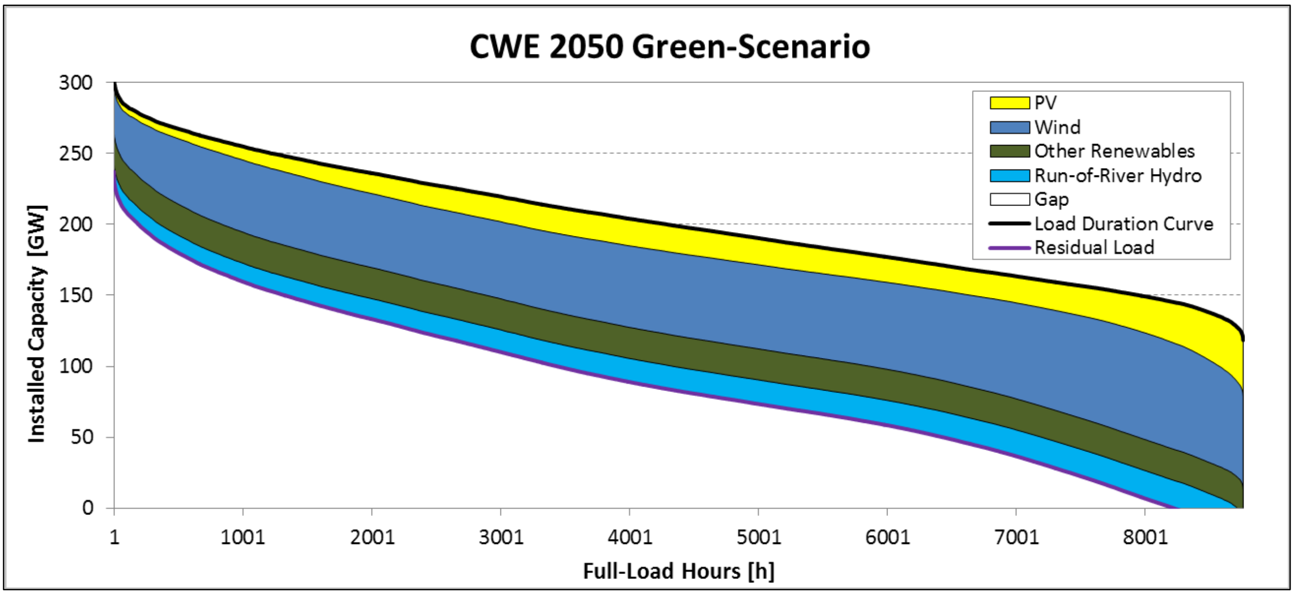

Figure 11: Load duration and residual load curve for the CWE region in the GREEN scenario in the year 2050

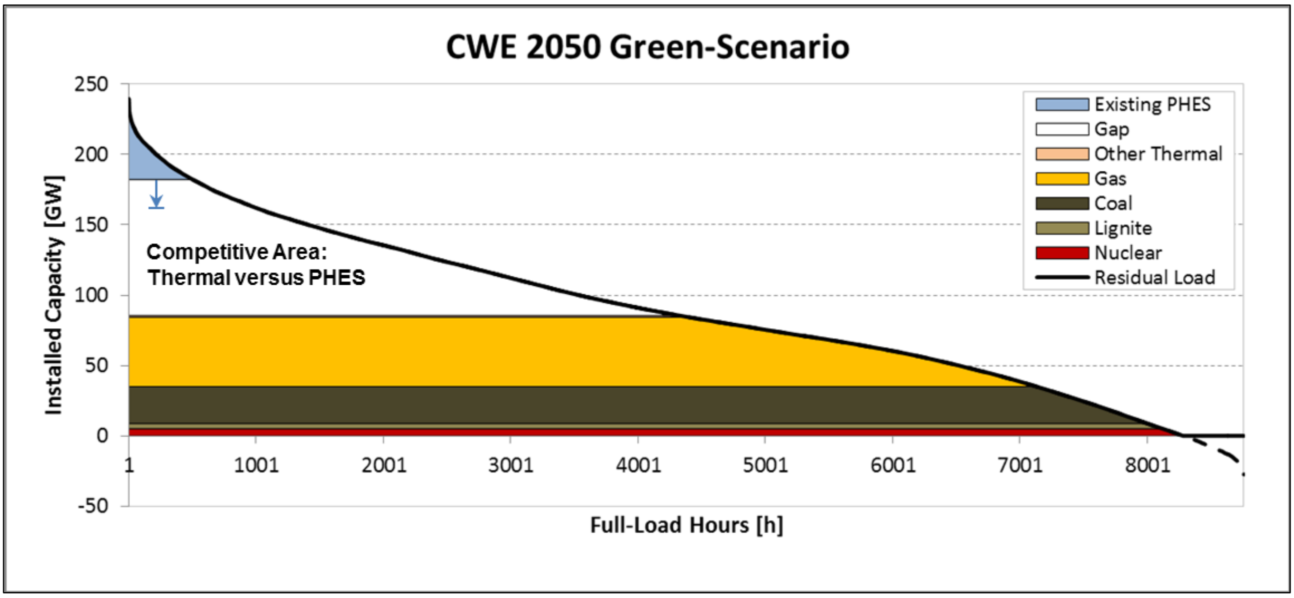

Figure 12: Coverage of the 2050 residual load of the CWE region with existing thermal power plants and PHES in the GREEN scenario

3.4 Iberian Peninsula (GREEN scenario 2050)

In the GREEN scenario RES-E feed-in exceeds electricity demand more than half the time of the year 2050 in the Iberian Peninsula (cf. Figure 13 and Figure 14). This RES-E excess generation can be used for (large-scale) electricity storage (e.g. this electricity might be available at low cost for pumping purposes in a PHES system) and / or for exports to neighbouring regions. Unlike thermal power plants, PHES systems can help fully utilising future RES-E generation by storing excess RES-E generation and "restoring" it when needed.

However, as already seen in the results of the BAU scenario in the year 2030, sufficient flexible generation capacities (gas power plants and PHES systems) are available in the system to cover the residual load.

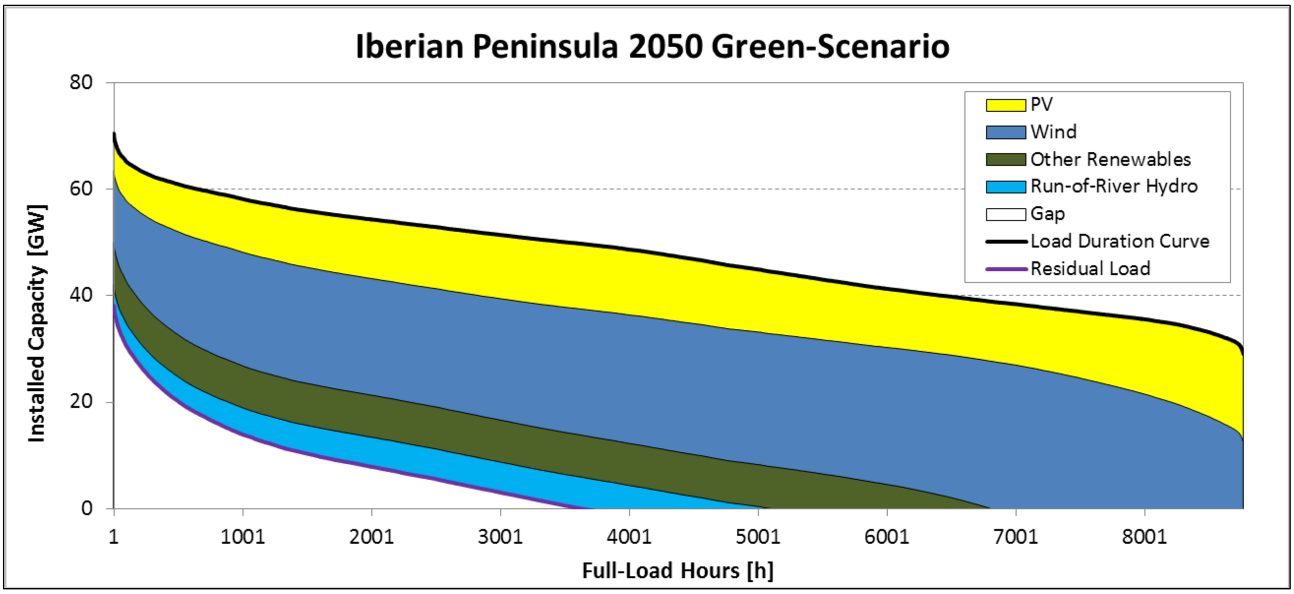

Figure 13: Load duration and residual load curve for the Iberian Peninsula in the GREEN scenario in the year 2050

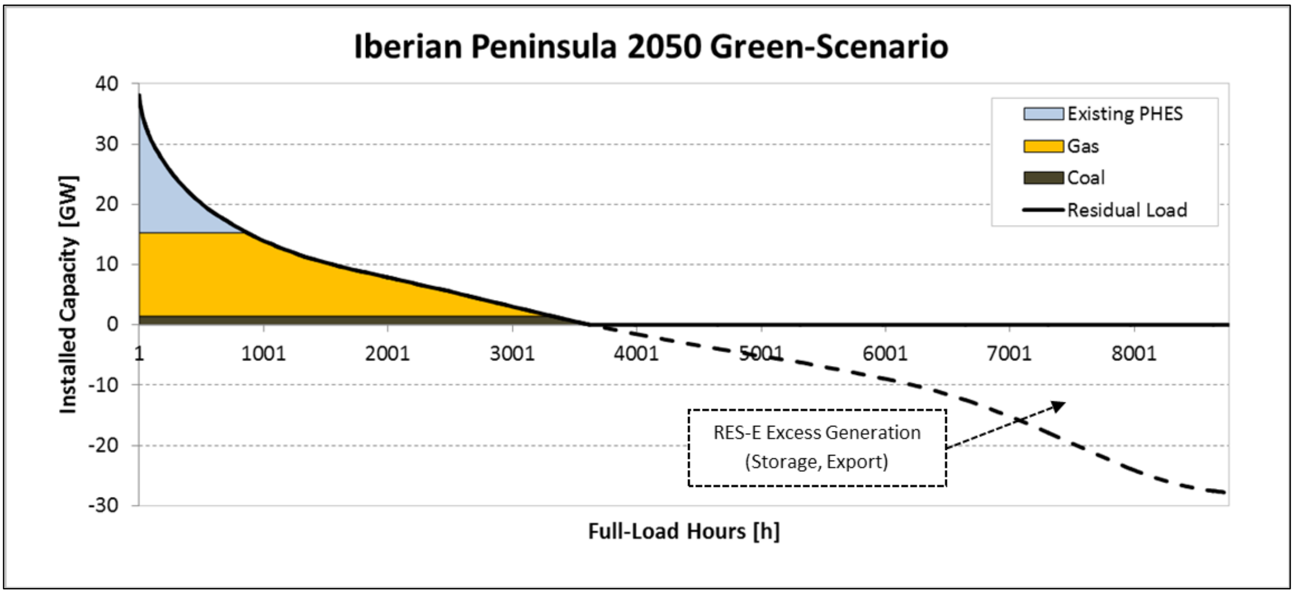

Figure 14: Coverage of the 2050 residual load of the Iberian Peninsula with existing thermal power plants and PHES in the GREEN scenario

3.5 Nordic Region (GREEN scenario 2050)

Due to high future RES-E deployment and large amounts of available (P)HES systems in the region, there is only a small gap of missing electricity generation capacity in the Nordic region in the GREEN scenario in the year 2050 (cf. Figure 15 and Figure 16). About one fourth of this gap could be filled with new (P)HES schemes.

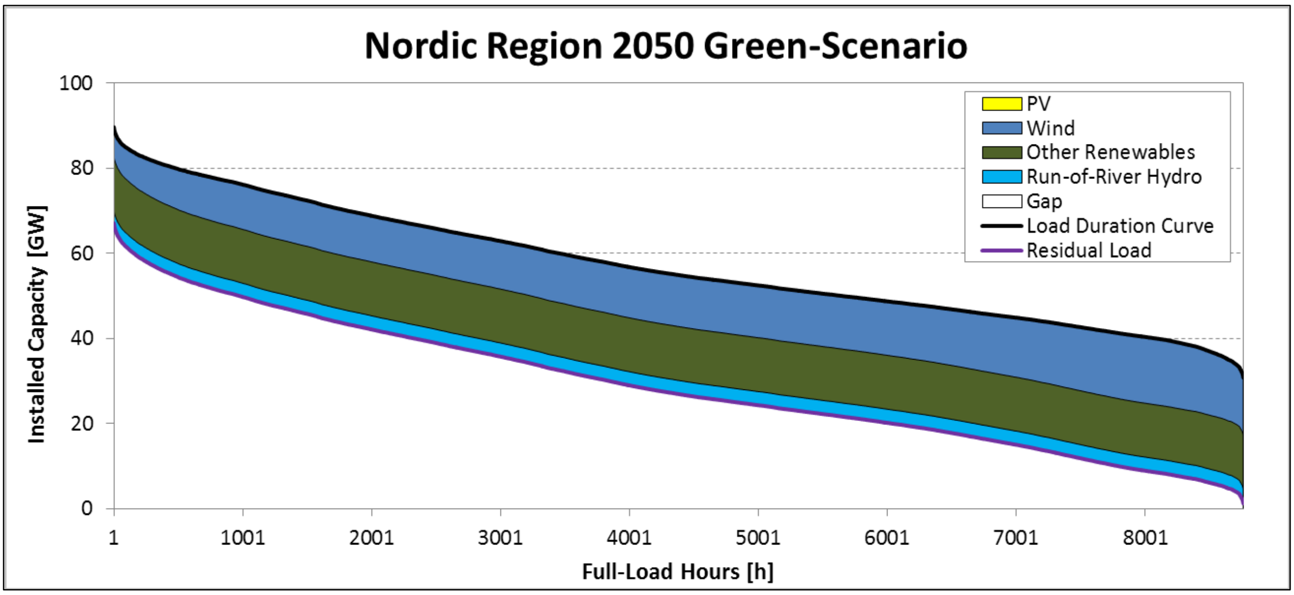

Figure 15: Load duration and residual load curve for the Nordic region in the GREEN scenario in the year 2050

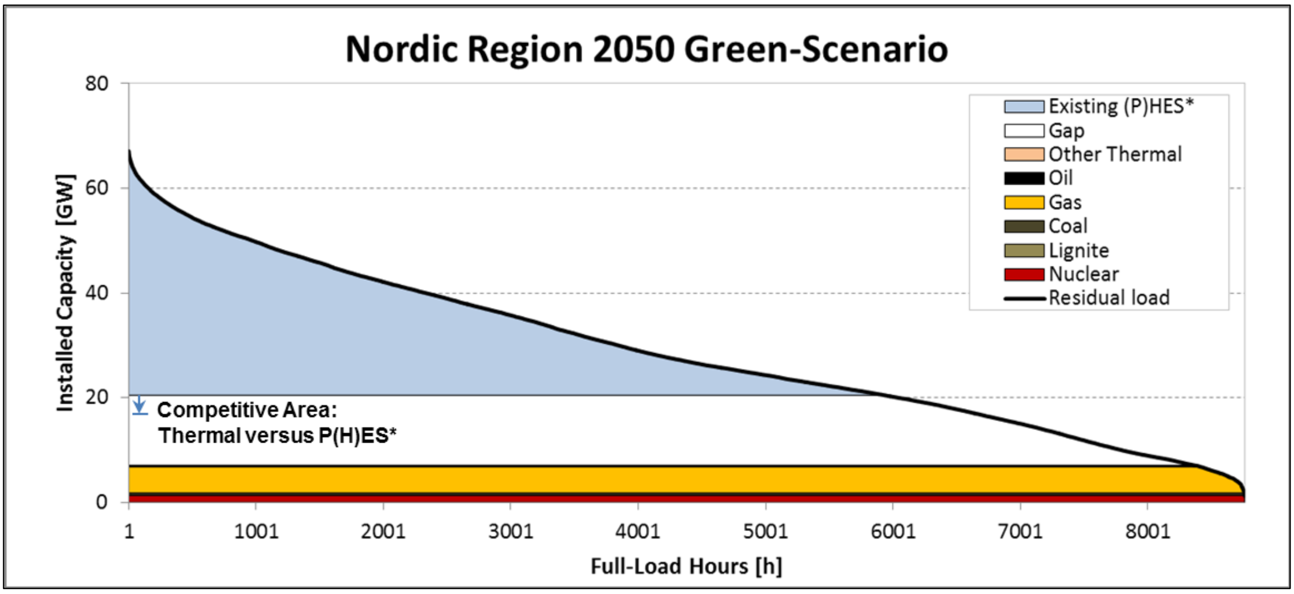

Figure 16: Coverage of the 2050 residual load of the Nordic region with existing thermal power plants and PHES in the GREEN scenario

3.6 Role of Cross-border Transmission Grid Expansion and Extreme Weather Events

The contribution of possible future transmission grid expansion between neighbouring European regions for better matching variable / intermittent wind generation and bulk EST / other flexible electricity generation technologies (e.g. balancing “stressed” continental European electricity systems with bulk storage energy from PHES from the Alps and Scandinavia) is qualitatively discussed in the following tables. Furthermore, the contribution of existing and new PHES and flexible thermal power plant units within a region and the management of extreme weather events within a region and between regions are assessed.

The result tables are shown for the previously highlighted European regions of CWE and the Iberian Peninsula (cf. Table 2 and Table 3). The result tables for remaining regions can be found in [1].

Table 2: Contribution of transmission expansion for mitigation of wind within the regions and management of extreme weather events for the CWE region

Contribution of Transmission Expansion for Mitigation of Wind within the Regions and Management of Extreme Weather Events						
CWE	Within the Region		Contributions from Outside ("Imports")		Contributions to other Regions ("Exports")	
	*Contribution in **CWE***		*Transmission Expansion to the **Nordic Region***		*Transmission Expansion to the **Nordic Region***	
	PHES	Thermal	Moderate	Significant	Moderate	Significant
	High (Existing)	High (Existing)	Limited	High (Anticorrelation Wind, PHES)	Low	Low (Anticorrelation Wind)
	High (New)	High (New)		Limited (Correlation Wind)		Low (Correlation Wind)
			*Transmission Expansion to **UK & Ireland***		*Transmission Expansion to **UK & Ireland***	
			Moderate	Significant	Moderate	Significant
			Limited	Limited (Anticorrelation Wind)	Low	Low (Anticorrelation Wind)
				Limited (Correlation Wind)		Low (Correlation Wind)
			*Transmission Expansion to the **Iberian Peninsula***		*Transmission Expansion to the **Iberian Peninsula***	
			Moderate	Significant	Moderate	Significant
			Limited	High (Anticorrelation Wind, Thermal)	Low	Low (Anticorrelation Wind)
				Limited (Correlation Wind)		Low (Correlation Wind)
			*Transmission Expansion to **Italy***		*Transmission Expansion to **Italy***	
			Moderate	Significant	Moderate	Significant
			Limited	High (Anticorrelation Wind, Thermal)	Low	Low (Anticorrelation Wind)
				Limited (Correlation Wind)		Low (Correlation Wind)
			*Transmission Expansion to the **Western Balkan***		*Transmission Expansion to the **Western Balkan***	
			Moderate	Significant	Moderate	Significant
			Limited	Limited (Anticorrelation Wind)	Low	Low (Anticorrelation Wind)
				Limited (Correlation Wind)		Low (Correlation Wind)
			*Transmission Expansion to **CEE***		*Transmission Expansion to **CEE***	
			Moderate	Significant	Moderate	Significant
			Limited	Limited (Anticorrelation Wind)	Low	Low (Anticorrelation Wind)
				Limited (Correlation Wind)		Low (Correlation Wind)

Table 3: Contribution of transmission expansion for mitigation of wind within the regions and management of extreme weather events for the Nordic Region and the Iberian Peninsula

Contribution of Transmission Expansion for Mitigation of Wind within the Regions and Management of Extreme Weather Events						
Nordic Region	Within the Region		Contributions from Outside ("Imports")		Contributions to other Regions ("Exports")	
	*Contribution in the **Nordic Region***		*Transmission Expansion to **UK & Ireland***		*Transmission Expansion to **UK & Ireland***	
	PHES	Thermal	Moderate	Significant	Moderate	Significant
	High (Existing)	High (Existing)	Limited	High (Anticorrelation Wind, Thermal)	Limited	High (Anticorrelation Wind, PHES)
	High (New)	High (New)		Limited (Correlation Wind)		Limited (Correlation Wind)
			*Transmission Expansion to **CWE***		*Transmission Expansion to **CWE***	
			Moderate	Significant	Moderate	Significant
			Low	Low (Anticorrelation Wind)	Limited	High (Anticorrelation Wind, PHES)
				Low (Correlation Wind)		Limited (Correlation Wind)
			*Transmission Expansion to **CEE***		*Transmission Expansion to **CEE***	
			Moderate	Significant	Moderate	Significant
			Limited	Limited (Anticorrelation Wind)	Limited	High (Anticorrelation Wind, PHES)
				Limited (Correlation Wind)		Limited (Correlation Wind)
			*Transmission Expansion to the **Baltic Region***		*Transmission Expansion to the **Baltic Region***	
			Moderate	Significant	Moderate	Significant
			Limited	Limited (Anticorrelation Wind)	Limited	High (Anticorrelation Wind, PHES)
				Limited (Correlation Wind)		Limited (Correlation Wind)
Iberian Peninsula	Within the Region		Contributions from Outside ("Imports")		Contributions to other Regions ("Exports")	
	*Contribution in the **Iberian Peninsula***		*Transmission Expansion to **CWE***		*Transmission Expansion to **CWE***	
	PHES	Thermal	Moderate	Significant	Moderate	Significant
	High (Existing)	High (Existing)	Low	Low (Anticorrelation Wind)	Limited	High (Anticorrelation Wind, Thermal)
	Low (New)	Low (New)		Low (Correlation Wind)		Limited (Correlation Wind)

In general, it can be observed that existing and new PHES and flexible thermal power plant units are strongly needed in the majority of the European electricity regions to cope with the effects of variable RES-E feed-in. Only in the Iberian Peninsula sufficient (flexible) power plant capacity is already in the electricity system, thanks to high investments in new gas-fired thermal power plants in the last 10 years and also due to high amounts of already implemented PHES schemes.

Due to a lack of available (flexible) power plant capacities in the future, the CWE region can hardly contribute to balancing services in neighbouring regions even in case of significant transmission grid expansion. However, imports from the Nordic region, the Iberian Peninsula and also Italy could help mitigating the effects of intermittent RES-E generation in the CWE region.

Because of its vast amounts of flexible (P)HES systems, the Nordic region could contribute to balance neighbouring European regions in case of significant transmission grid expansion. If additional generation capacities are needed, UK & Ireland could contribute with their flexible thermal power plant portfolio.

Since the Iberian Peninsula is located on the outer edge of the European electricity system, its importing / exporting capabilities from / to neighbouring regions are limited. However, in case of significant transmission grid expansion to the CWE region, the Iberian Peninsula could export electricity from flexible gas-fired thermal power plant units.

4. Conclusions

Due to age-related phase-out of thermal power plants in the future additional new power plant capacities are needed in many electricity regions already up to the year 2030. These gaps of electricity generation capacity can be either filled up with new PHES systems (as far as additional potential is available in the region) or new thermal power plants. The technology type finally to be used depends on the economics of the power plant (i.e. electricity generation cost, depending on primary fuel costs, CO_2 price, etc.). The most economic new thermal power plant technology is also the competitor / benchmark for new PHES power plants in the region.

The Iberian Peninsula only has sufficient flexible generation capacity (gas power plants and PHES systems) available in the system to cover the residual load also in the long-term (due to large investments in gas-fired power plants in the last ten years). Furthermore, in the GREEN scenario RES-E feed-in exceeds electricity demand more than half the time of the year 2050 in the Iberian Peninsula. This excess RES-E generation can be used for (large-scale) electricity storage and / or for exports to neighbouring European regions. Because of its vast amounts of flexible (P)HES systems, also the Nordic region could significantly contribute to balance the electricity systems of neighbouring regions in case of significant transmission grid expansion and negative correlation of wind between the regions.

In general, it can be observed that existing and new PHES (and additional flexible thermal power plant units) are strongly needed in almost all of the European electricity market regions to (partly) cover the future electricity generation gap. Unlike fossil fuel-fired thermal power plants, PHES systems can provide flexibility without additional CO_2 emissions and can help fully utilising future RES-E generation.

Both technology options, bulk EST as well as transmission grid expansion, are needed to perfectly operate future European electricity systems with high shares of RES-Electricity. The preferable measure (transmission expansion versus bulk EST) is dependent on the region in Europe and will mainly be decided via a cost / benefit analyses. However, both technology options suffer from the same problem of low social acceptance, which will have to be overcome anyway.

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