www.store-project.eu

Facilitating energy storage to allow high penetration of intermittent renewable energy

Contribution of Bulk Energy Storage in Future Electricity Systems Facilitating Renewable Energy Expansion

Deliverable 2.3

(Source: SwissWinds)

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)

Author(s)		
Name	**Organisation**	**E-mail**
Karl Zach	EEG	zach@eeg.tuwien.ac.at
Hans Auer	EEG	auer@eeg.tuwien.ac.at
Günther Körbler	EEG	koerbler@eeg.tuwien.ac.at
Georg Lettner	EEG	lettner@eeg.tuwien.ac.at

Table of Contents

Supported by INTELLIGENT ENERGY EUROPE

List of Abbreviations

(P)HES	…	(Pumped) Hydro Energy Storage – i.e. conventional HES as well as PHES
AA-CAES	…	(Advanced-) Adiabatic Compressed Air Energy Storage
BAU	…	Business-As-Usual
CAES	…	Compressed Air Energy Storage
C_{Cert}	…	CO_2-certificate price
CCGT	…	Combined-Cycle Gas Turbine
CEE	…	Central Eastern Europe (i.e. Poland, Czech Republic, Slovakia, Hungary)
$C_{el, Thermal}$	…	Electricity generation costs of thermal power plant
C_{Fuel}	…	Primary fuel costs
C_{Inv}	…	Investment costs
$C_{O\&M}$	…	Operation and maintenance costs
CO_2	…	Carbon dioxide
CSP	…	Concentrated Solar thermal Power
CWE	…	Central Western Europe (i.e. France, the Netherlands, Luxembourg, Belgium, West Denmark, Germany, Switzerland and Austria)
EC	…	European Commission
E_{CO2}	…	Specific CO_2-emissions
EST	…	Electricity Storage Technology
EU	…	European Union
GW	…	Giga Watt
HES	…	Hydro Energy Storage (dam- or barrage-hydro power plant)
km^2	…	Square kilometre
kW	…	Kilo Watt
MW	…	Mega Watt
MWh	…	Mega Watt Hour
O&M	…	Operation and Maintenance
OCGT	…	Open-Cycle Gas Turbine
PHES	…	Pumped Hydro Energy Storage
PV	…	Photovoltaics
RES-E	…	Renewable Energy Sources for Electricity generation
SEE	…	South-Eastern Europe (i.e. Romania, Bulgaria and Greece)
t CO_2	…	Ton of CO_2 (i.e. 1000 kg of CO_2)
T	…	Annual full-load hours
TSO	…	Transmission System Operator
TWh	…	Tera Watt Hour

TYNDP	…	Ten Year Network Development Plan (ENTSO-E)
UK	…	The United Kingdom
WP	…	Work-Package
yr	…	Year
α	…	Annuity factor
η_{el}	…	Electric efficiency

Executive Summary

This document, Deliverable 2.3 (D2.3) of the stoRE project, gives an overview on the contribution of bulk energy storage technologies (EST), namely compressed air energy storage (CAES) and pumped hydro energy storage (PHES), in future European electricity systems facilitating large-scale renewable electricity expansion. This report is structured into two main parts.

Part I (Section 2) identifies the geographical allocation of future potentials of bulk EST and future large-scale wind deployment across Europe. 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). 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. 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 potentials for further deployment of PHES systems. Particularly Luxembourg, Switzerland and Austria have a very high PHES potential in relation to their land size.

Future European wind deployment scenarios were generated based on modelling results derived from the Green-X RES-E deployment simulation tool. Green-X provides future scenarios on annual RES-E capacity installations and electricity generation per country under a variety of different possible policy settings and constraints. Two different future RES-E deployment scenarios were generated: A business-as-usual scenario (BAU) with moderate increase of RES-E deployment and an environmental friendly scenario (GREEN) with high increase of RES-E deployment in Europe. Especially Germany, Spain, the United Kingdom and France have very high installed wind capacities in the year 2050, whereas most Balkan & Baltic countries show low future wind deployment in both scenarios only.

In order to take 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 is coincident with the definition of the different European regions in the relevant EC documents (EC, 2007) and (EC, 2010) (EC infrastructure package) and the ENTSO-E's “Ten Year Network Development Plan (TYNDP)” (ENTSO-E, 2010a).

Part II (Section 3) of this report provides estimates on the possible direct benefits and future contributions of bulk EST implementation to balance incumbent regional electricity systems. Doing this, 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. The residual load curves of nine different European electricity regions for the years 2020, 2030 and 2050 and for two different scenarios (low / high RES-E expansion) were derived. To be able to roughly estimate the possible direct benefits of bulk EST implementation and their possible future contribution to an incumbent regional electricity system, the existing thermal power plant-portfolio within the different European electricity market regions was also considered. To be able to do so, the age structure and the phase-out of the existing thermal power plant-portfolio were generated from the PLATTS database (PLATTS, 2010) for several different electricity market regions. The possible coverage of the residual load curve with existing thermal power plants and bulk EST was

Supported by INTELLIGENT ENERGY EUROPE

analysed. For better readability, the results presented in this report focus on four European regions, namely Central Western Europe (CWE), Central Eastern Europe (CEE), the Iberian Peninsula and the Nordic region, and for years 2030 and 2050. The results of the other five regions are given in Appendix 4 of this document.

Mainly as a result of age-related phase-out of thermal power plants, additional new power plant capacities are needed to meet electricity demand in almost all European electricity market regions already in 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 a region) or new thermal power plants. The technology type to be mainly 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 system implementations in a region.

However, in the electricity market regions of the Iberian Peninsula and Italy sufficient (thermal) power is available (i.e. no capacity gap between generation and demand). This has two reasons: On the one hand, high RES-E deployment in the regions (especially wind, but also PV) and, on the other hand, large amounts of still existing thermal power plants in the year 2030 / 2050, due to high investments in gas-fired thermal power plants in the last ten years in these regions.

In some European regions in the GREEN scenario RES-E feed-in exceeds electricity demand sometimes in the year 2050. 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 exports to neighbouring regions.

Furthermore, the analysis in this document incorporates also the estimation of the contribution of possible future corridors on transmission interconnectors on ENTSO-E’s transmission grid for load smoothing and bringing together variable / intermittent wind generation and bulk EST in different European electricity market regions. Furthermore, the effects of extreme weather events (positive / negative correlation of wind between the regions) are also qualitatively discussed.

In general, it can be observed that existing and new PHES and flexible thermal power plant units are strongly needed in almost all of the European electricity market regions to cope with the effects of variable RES-E feed-in. In the UK & Ireland region PHES systems will have a little contribution to the electricity system only, because of low future PHES potentials in comparison to the overall electricity demand / generation in the region.

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.

The CEE region is very similar to the CWE region in terms of possible contribution to neighbouring electricity market regions, as it also has only limited capability. The region could profit from Nordic, SEE and Western Balkan PHES capacities in case of a negative correlation of wind between the regions.

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

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 also export electricity from flexible gas-fired thermal power plant units.

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.

1 Introduction

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. In the stoRE project the focus of analysis and discussions is set predominantly on bulk energy storage technologies (EST), namely pumped hydro energy storage (PHES) and compressed air energy storage (CAES)[1].

Bulk EST are expected to be one of the key enabling technologies for the integration of large amounts of variable / intermittent electricity generation from renewable energy sources (RES-E). 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)[2] can mitigate many challenges that arise from high shares of variable / intermittent RES-E generation in the electricity system. Furthermore, bulk EST could also play an important role in optimising the physical and financial functioning of electricity markets and the corresponding commercial energy trading activities[3].

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

This document, Deliverable 2.3 (D2.3), gives a rough overview on the contribution of bulk EST in future European electricity systems facilitating significant renewable energy expansion. This report is structured into two main parts.

Section 2 identifies the geographical allocation of future potentials of bulk EST and future large-scale wind deployment in Europe. 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). Future European wind deployment scenarios were generated based on modelling results derived from the Green-X RES-E deployment simulation tool[4].

Section 3 of this report provides estimates of the possible direct benefits and the possible future contribution of bulk EST implementation to balance incumbent regional electricity systems. For this, 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. The residual load curves of nine different European electricity regions for the years 2020, 2030 and 2050 and for two different scenarios (low / high RES-E expansion)[5] were derived. The possible coverage of

---

[1] For a complete picture of energy storage options see Deliverable 2.1 (D2.1) of the stoRE project, which also provides a brief overview of other (non-bulk) EST being outside the scope of the stoRE project.

[2] Other benefits of bulk EST, i.e. black start capability, area control, frequency response (secondary and tertiary control) etc., are described in Deliverable 2.1 in detail.

[3] See Deliverable 2.2 (D2.2) of the stoRE project for more details about the role of bulk EST in future electricity systems with high shares of RES-E generation.

[4] Used and updated within many European projects within the last 10 years (e.g. recently: RE-Shaping http://www.reshaping-res-policy.eu/). See http://www.green-x.at and Huber et al. (2004) for more details.

[5] For better readability, the results presented in this report focus on four regions and the years 2030 and 2050 only. The results of the remaining five regions are given in Appendix 4 of this report.

the residual load curve with existing thermal power plants and bulk EST was analysed.

In this document, and within WP2 of the stoRE project in general, the analysis focus on nine different European electricity regions, established on the basis of relevant EC documents (EC, 2007) and (EC, 2010) (e.g. EC infrastructure package) and the ENTSO-E's "Ten Year Network Development Plan (TYNDP)" (ENTSO-E, 2010a). A more detailed analysis methodology on country-level for the six different target countries will be developed within WP5 of the stoRE project.

The second part of section 3 analyses the contribution of possible future corridors on transmission interconnectors on ENTSO-E's transmission grid for load smoothing and bringing together variable / intermittent wind generation and bulk EST in different European electricity market regions. Furthermore, the effects of extreme weather events (positive / negative correlation of wind) are qualitatively discussed.

Overall conclusions from the analysis carried out in this report are drawn in section 4.

Appendix 1 contains the geographical allocation of future bulk EST potentials and large-scale wind deployments within the target countries. Appendix 2 gives (P)HES potential and wind deployment data from the analysis of section 2. Appendix 3 provides parameter settings for the economic trade-off analysis of the different types of thermal power plant technologies from the trade-off analysis of section 3.2.4. Finally, in Appendix 4 more results from the analysis of section 3.3 and 3.4 are presented.

.

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

2.1 Overview

The estimation of the future potential of bulk EST implementation and its contribution to mitigate variability and intermittency caused by large-scale RES-E generation is not based on detailed modelling of the European electricity system, but rather on a review and synthesis of existing work, studies and modelling results on this topic. The time horizon for this potential analysis is mainly the target years 2020, 2030 and 2050.

After estimating the future potential for bulk EST (section 2.2), the geographical allocation of future large-scale wind deployment in several European countries for the years 2020, 2030 and 2050 are generated based on modelling results derived from the Green-X RES-E deployment simulation tool (section 2.3). 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[4].

Due to physical constraints in the European transmission grid, electricity transfer between countries is limited, with the consequence of different wholesale electricity markets / prices. To take this into account in the analysis, European countries were clustered into nine different electricity regions (see section 2.4).

The analysis of spatial dispersion of EST potential and wind deployment in different European regions is a precondition to be able to conduct the “matching” exercise of chapter 3.

2.2 Geographical Allocation of Future Potentials for Bulk Energy Storage Technologies in Europe

The geographical allocation of future potentials for bulk EST in Europe is estimated based on the most relevant existing work and studies on country-level as well as on European level:

- PLATTS – European electric power plant database (PLATTS, 2010)
- ENTSO-E – System Adequacy Forecast (ENTSO-E, 2010b)
- EURELECTRIC – Hydro in Europe report (EURELECTRIC, 2011)
- National renewable energy action plans (NREAP) (Beurskens et al, 2011)
- Green-X database[4]
- JRC – PHES: potential for transformation from single dams (JRC, 2012)

Detailed data for the target countries were made available by the respective stoRE project partners.

The result of this potential estimation for bulk EST in Europe is shown in Figure 1. Due to lack of data sources on future deployment and potential of CAES systems (currently only one operating

CAES power plant and one under development in Germany), Figure 1 shows estimations on future potentials of (P)HES systems in Europe (including already existing (P)HES systems) only. However, CAES systems might also play an important role in the future European electricity system, but the utilization potential of CAES systems is dependent on the availability of appropriate underground air storage capacities (especially salt caverns) and on further technological developments needed in order to reach higher overall efficiencies and to eliminate the need for using additional fossil fuels (i.e. AA-CAES)[6].

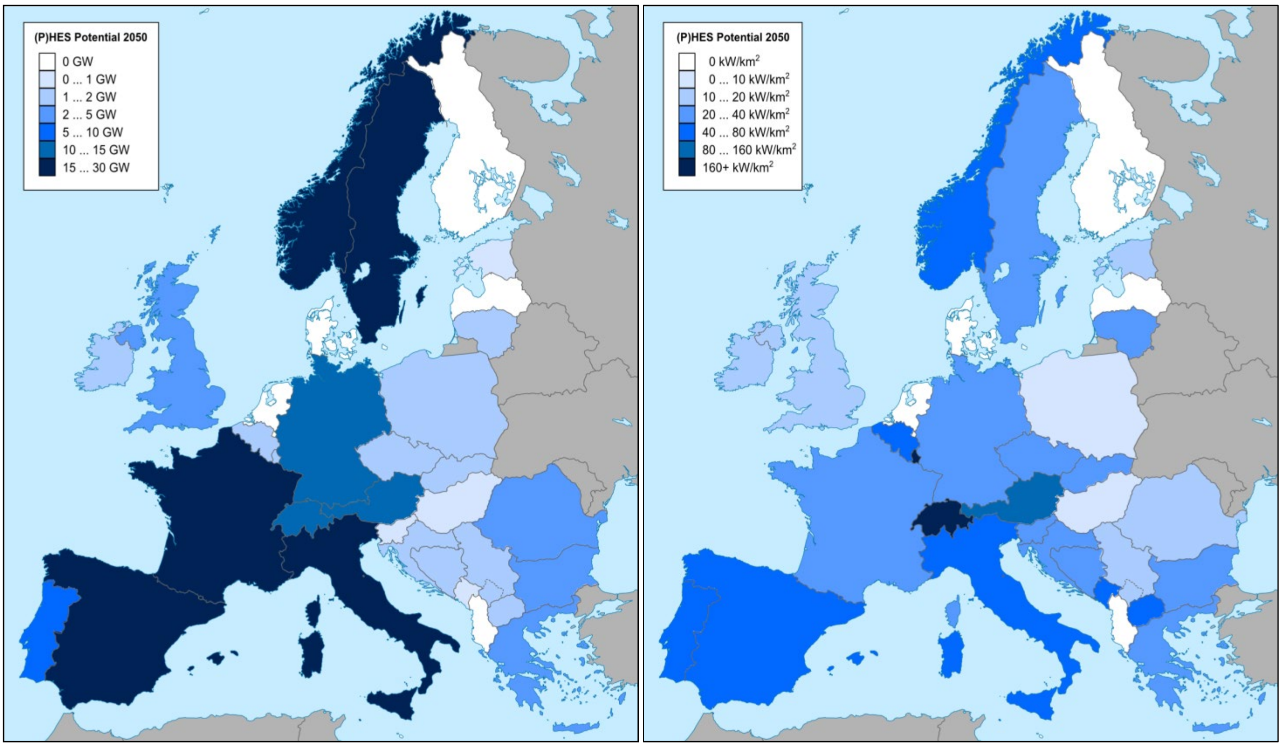


Figure 1: (P)HES potential in Europe until the year 2050: Power capacity per country [GW] (left) and power capacity per land area per country [kW/km^2] (right) (Data source: see text above)[7]

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[8].

Norway, often referred to as the “green battery” of Europe, has almost half of Europe’s reservoir capacity, based on the topographical advantage of high mountainous lakes or reservoirs. Typically 60 - 70% of Norwegian’s average annual hydropower generation (123 TWh) is produced by (conventional) HES power plants offering high flexibility in electricity generation. Since the Norwegian electricity generating system already comprises a lot of flexibility through its

---

[6] See Deliverable 2.1 of the stoRE project for more details.

[7] See Appendix 2 for input data tables.

[8] No data is available for Albania.

hydropower plants, the construction of new PHES (or upgrading of existing HES) power plants has so far not been economically profitable. This is also a reason why Norway currently has 1,336 MW of PHES systems only, occasionally used to pump seasonal excess water into higher reservoirs (EURELECTRIC, 2011).

2.3 Geographical Allocation of Future Large-scale Wind Deployment in Europe

The geographical allocation of future large-scale wind deployment (on- and offshore) in European countries for the years 2020, 2030 and 2050 are generated based on modelling results derived from the Green-X (Huber et al, 2004) 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.

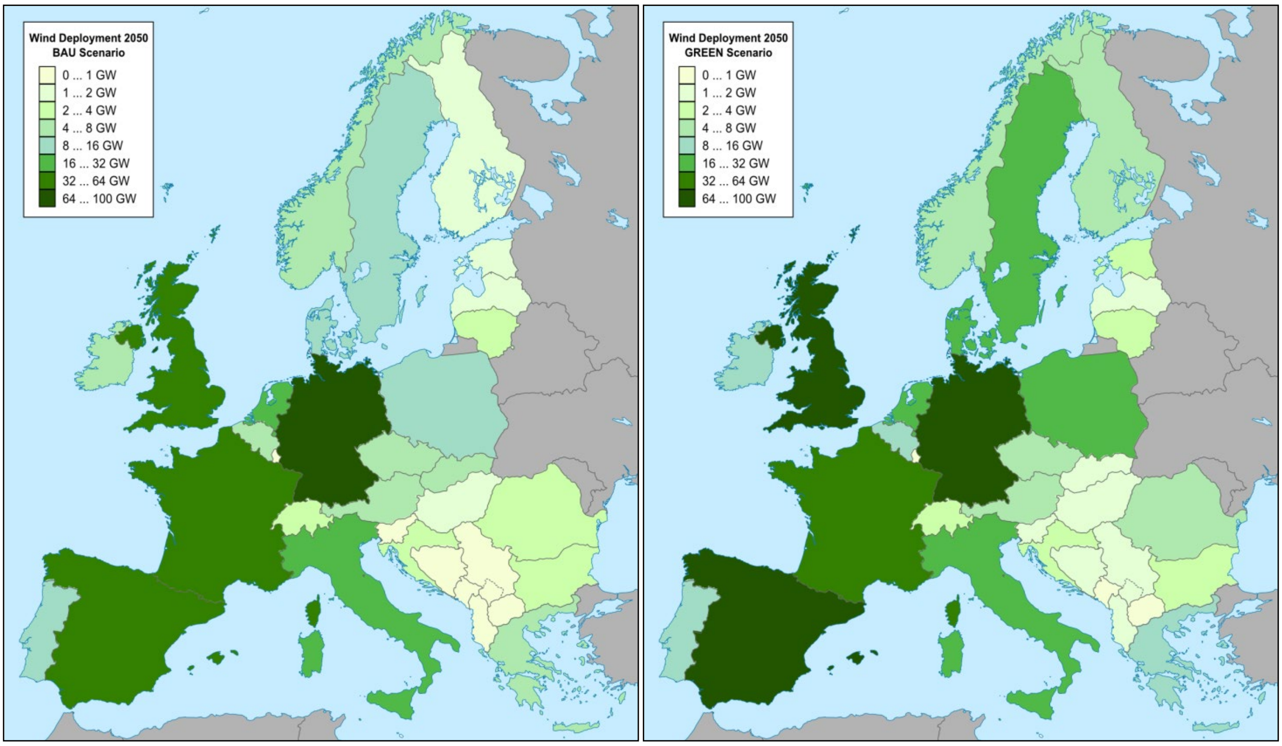


Figure 2: Wind deployment in Europe in the year 2050: Comparison of BAU scenario (left) and GREEN scenario (right) (Source: EEG) [9]

For the analyses within WP2 of the stoRE project, two different future RES-E deployment scenarios were generated: 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.[10] A comparison of the generated wind deployment in European countries in

---

[9] See Appendix 2 for input data tables and additional figures showing wind power capacity per land area per country [kW/km^2].

[10] See chapter 3 for more details about the scenario assumptions.

Supported by INTELLIGENT ENERGY EUROPE

the year 2050 in the two different scenarios is given in Figure 2. It can be seen that, in absolute terms, especially Germany, Spain, the United Kingdom 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.

In addition to the shown geographical allocation of (P)HES potentials and future wind deployment in Europe, also more detailed maps for the six target countries of the stoRE project[11] were established. There, the geographical allocation of future development potentials of bulk EST and future large-scale wind generation centres are indicated within the target country. The maps are given in Appendix 1.

2.4 European Electricity Market Regions

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):

- Iberian Peninsula: Portugal and Spain
- Central Western Europe (CWE): France, the Netherlands, Luxembourg, Belgium, West Denmark, Germany, Switzerland and Austria
- Central Eastern Europe (CEE): Poland, Czech Republic, Slovakia and Hungary
- South-Eastern Europe (SEE): Romania, Bulgaria and Greece
- Western Balkan: Slovenia, Serbia, Croatia, Bosnia & Herzegovina, Republic of Macedonia and Montenegro
- Italy
- The United Kingdom (UK) & Ireland
- Nordic Region: Norway, Sweden, Finland and East Denmark
- Baltic Region: Lithuania, Latvia and Estonia

This clustering coincides with relevant EC documents (EC, 2007) and (EC, 2010) (e.g. EC infrastructure package) and the ENTSO-E's "Ten Year Network Development Plan (TYNDP)" (ENTSO-E, 2010a) and is shown in Figure 3. Additionally, Figure 3 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.

Obviously, in most electricity market regions expected wind deployment in the year 2050 exceeds possible (P)HES deployment by far. However, it is not necessary that both technologies achieve the same deployments in order to have sufficient flexibility in the electricity system. On the one

---

[11] stoRE target countries: Austria, Denmark, Germany, Greece, Ireland and Spain.

hand, not every single GW of installed wind capacity (or other variable RES-E generation technologies like PV) has to be backed up by the same amount of (P)HES capacity. E.g., wind generation in high electricity demand periods need not to be shifted. And on the other hand, there might be other flexibility options available within the electricity system, like fast ramping CCGT's[12] being also able to cope with variable RES-E generation. Therefore, the shown wind and (P)HES deployments in Figure 3 only can be interpreted as rough indicators on the need of other flexibility options required within the regions.

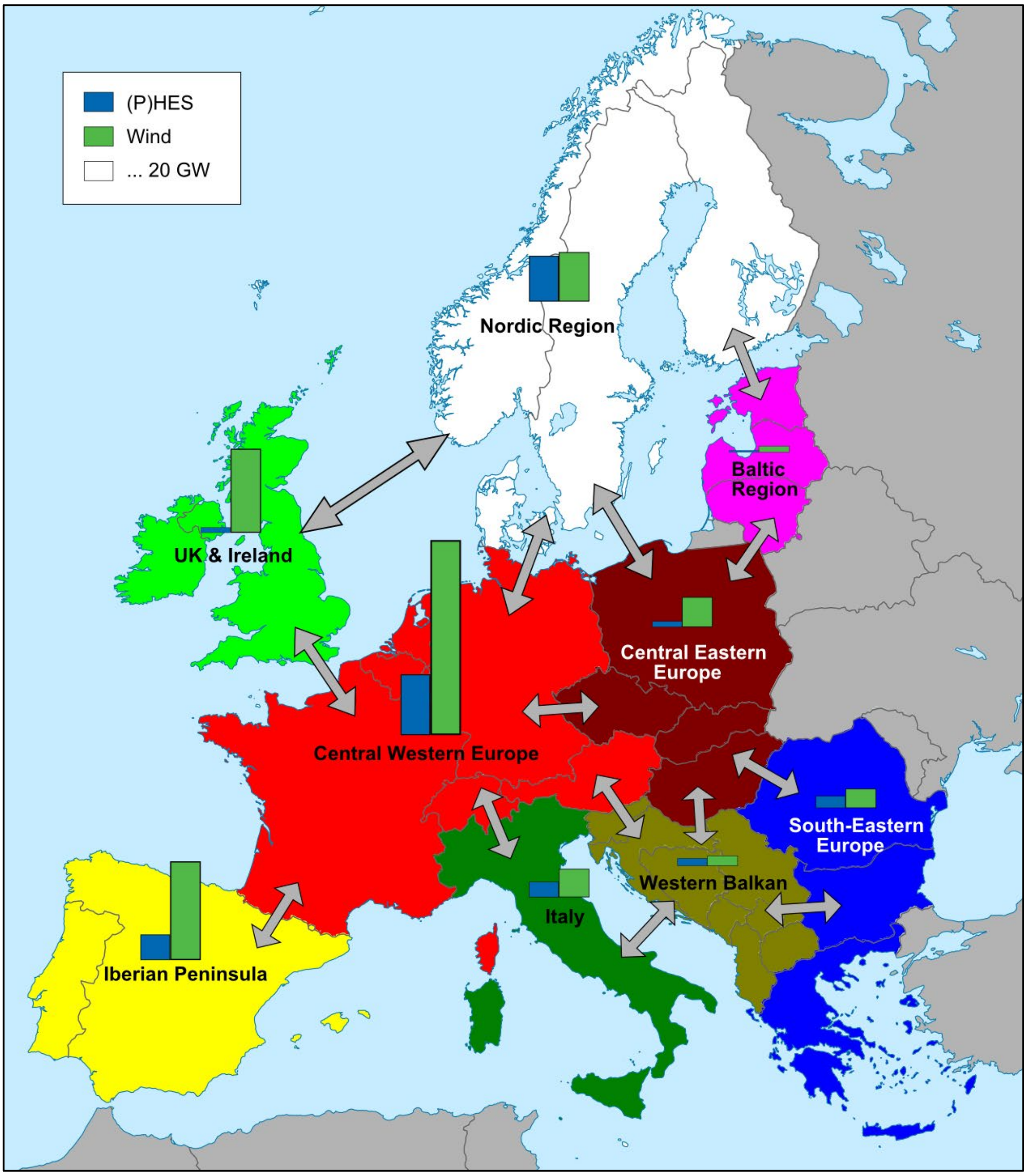


Figure 3: Clustering of countries to nine different European electricity regions (Source: EEG)[7]

---

[12] See Deliverable 2.2 of the stoRE project for more details.

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

3.1 Overview

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 2020, 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.

As previously mentioned, within Task 2.3 of the stoRE project the focus of the analysis is on European electricity region-level. A more detailed analysis methodology on country-level for the six different target countries will be developed within WP5 of the stoRE project.

In the following sections of chapter 3, the modelling approach, input data and selected results of the analysis for the years 2030 and 2050 are described in detail. Furthermore, the contribution of possible future corridors on transmission interconnectors on ENTSO-E's transmission grid for bringing together variable / intermittent wind generation and bulk EST in different European regions (e.g. balancing "stressed" continental European electricity systems with bulk storage energy from PHES from the Alps and Scandinavia) are discussed both quantitatively and qualitatively. Finally, also the effects of extreme weather conditions (positive and negative correlation of wind) are subject to qualitative analyses and discussions.

3.2 Methodology

3.2.1 Derivation of "load duration" and "residual load" curve in the different European electricity market regions for the years 2020, 2030, 2050

For the derivation of the load duration curves and residual load curves in the different European electricity market regions for the years 2020[13], 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 (ENTSO-E, 2012)[14]. 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[15]. The ENTSO-E electricity demand data is including the network losses but excluding consumption for PHES (pumping mode) and consumption of generation auxiliaries. With this data the regional load duration curves were established for the years 2020, 2030 and 2050 (cf. Figure 5).

---

[13] For better readability, results for the year 2020 are not presented in this report. However, they are available separately in a working document.

[14] No data was available for Albania (therefore not included in the analysis).

[15] Eastern Europe: CEE, Western Balkan, Baltic region, SEE without Greece.

Supported by INTELLIGENT ENERGY EUROPE

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

	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 (Huber et al, 2004) 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 4. 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 (see below).

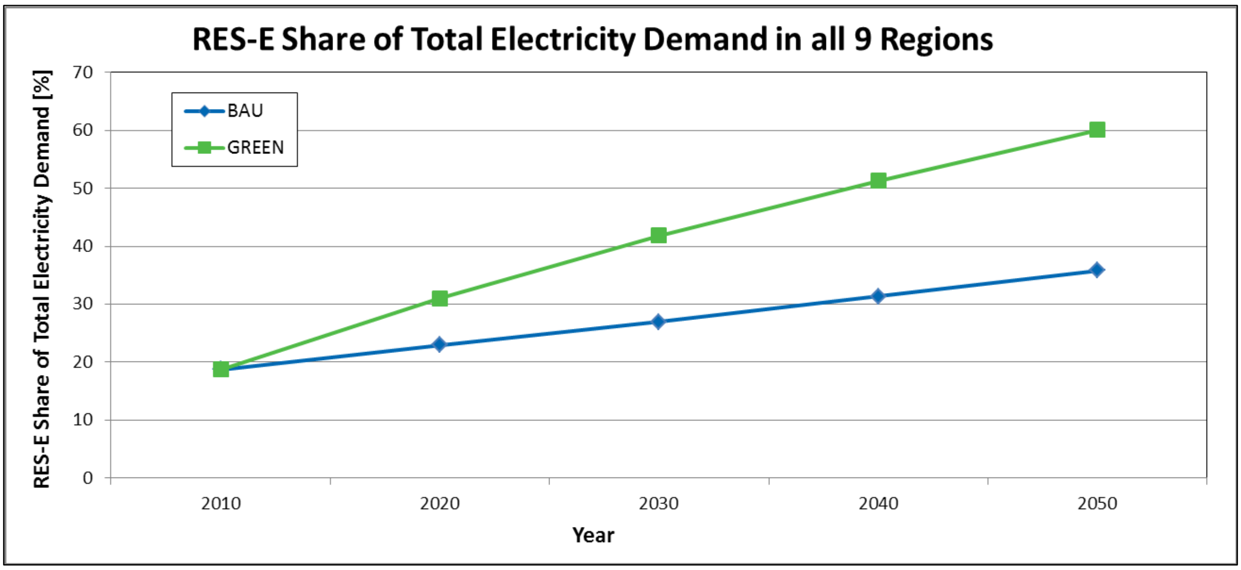


Figure 4: RES-E share of total electricity demand in all nine electricity market regions (Source: EEG)

- ***Hourly PV Electricity Generation:*** To establish hourly PV electricity generation within each region, hourly global solar radiation data were used from SoDa (SoDa, 2012). 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 5).
- ***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 (IWES, 2009) was taken as a reference and was used to derive hourly wind data for all regions (cf. Figure 5).

Supported by INTELLIGENT ENERGY EUROPE

- ***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 5).
- ***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 5).

An example for the established set of regional residual load curves is shown in Figure 5, where the load duration and residual load curve for the CWE region in the year 2030 is given. In general, the residual load curves (purple line in Figure 5) 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.

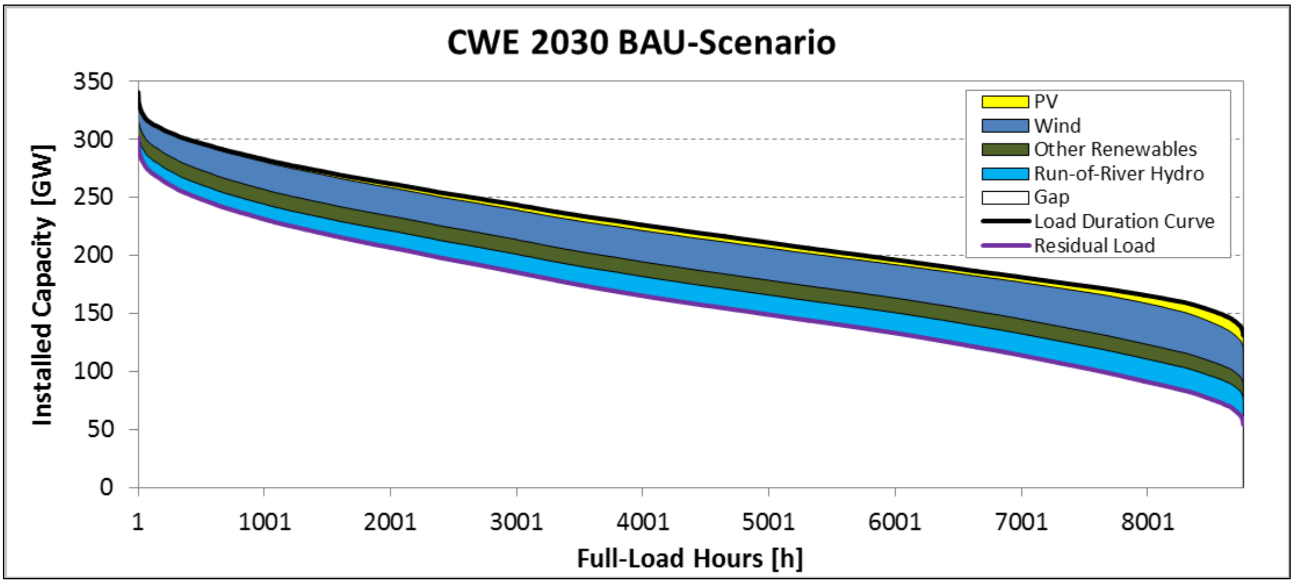


Figure 5: Load duration and residual load curve for the CWE region in the BAU scenario in the year 2030 (Source: see text)

3.2.2 Consideration of the age structure of the existing thermal power plant portfolio for the years 2020, 2030, 2050

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 6 for an example) were generated from the PLATTS database (PLATTS, 2010) for all different electricity market regions. Installations of new thermal power plant capacities up to the year 2015 are already considered within the database.

Supported by INTELLIGENT ENERGY EUROPE

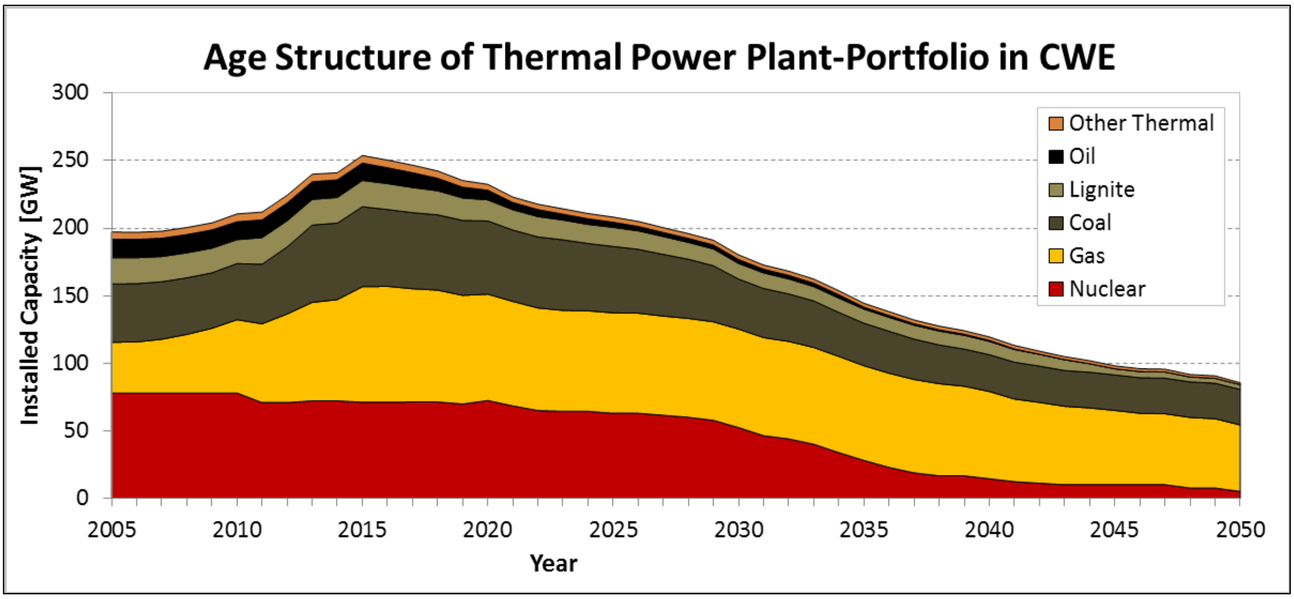


Figure 6: Age structure of the thermal power plant-portfolio in the CWE region (Data source: PLATTS, 2010)

Figure 6 shows an example of the status quo of the age structure of the thermal power plant portfolio in the CWE region. It can be seen that – ceteris paribus - the majority of nuclear capacities phase out by 2040 and only few new gas power plants are constructed until 2015 in the CWE region. The age structures of the thermal power plant-portfolio of all other European electricity market regions are given in Appendix 4.

3.2.3 *Coverage of the future residual loads with existing thermal power plants and PHES in the years 2020, 2030, 2050*

After deriving the age structure of the thermal power plant-portfolio in the different regions, established residual load curves for the years 2020, 2030 and 2050 were “filled-up” with the still existing thermal power plant capacities (cf. Figure 7). 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 7). 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 (see white area in Figure 7) an economic trade-off analysis between the different types of new thermal power plants has been conducted (see section 3.2.4). The most economic new thermal power plant type is the competitor / benchmark for new PHES power plants.

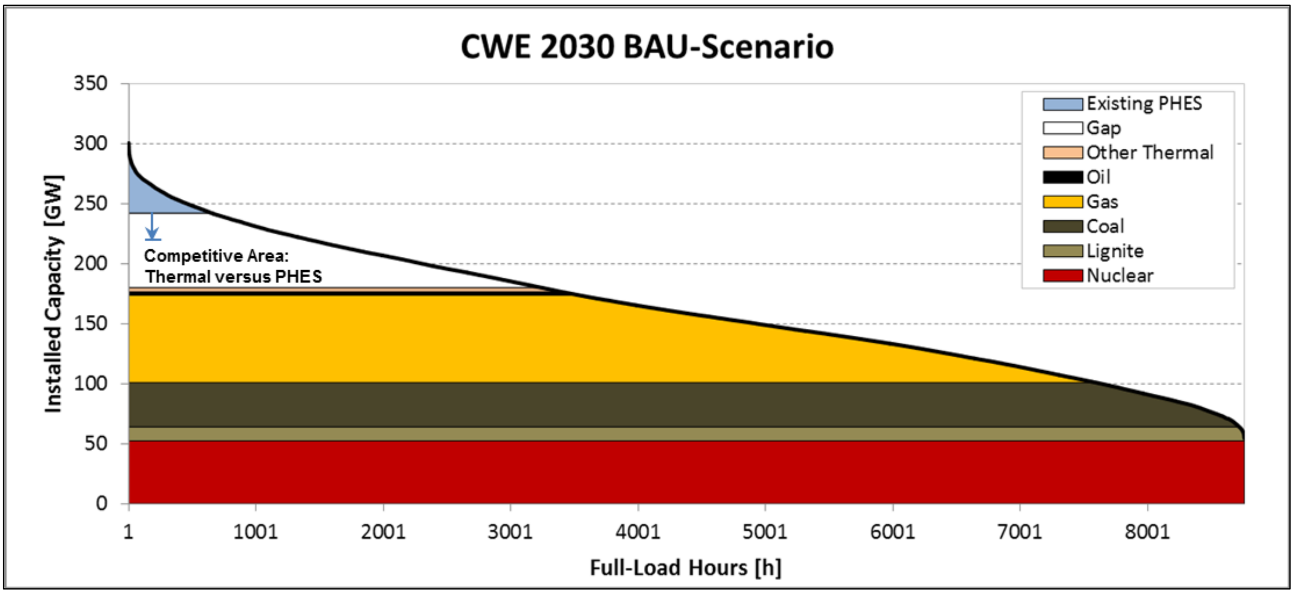


Figure 7: Coverage of the 2030 residual load of the CWE region with existing thermal power plants and PHES in the BAU scenario (Source: EEG)

Figure 7 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 in this scenario[16]. 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.

3.2.4 Economic trade-offs between the different types of new thermal power plants to fill the missing generation gap

To analyse the economic trade-off between the different types of new thermal power plants in the competitive area, the (long-run marginal) electricity generation costs of the different technologies were calculated based on the following formula:

$$C_{el,Thermal} = \frac{\alpha * C_{Inv}}{T} + \frac{C_{Fuel}}{\eta_{el}} + \frac{C_{O\&M}}{T} + \frac{C_{Cert} * E_{CO2}}{\eta_{el}}$$

$C_{el,\ Thermal}$ … Electricity generation costs of thermal power plant
α … Annuity factor[17]
C_{Inv} … Investment costs

---

[16] Certainly, also higher RES-E deployment (as e.g. in the GREEN scenario) would lower this capacity gap.

[17] $\alpha = \frac{i * (1+i)^P}{(1+i)^P - 1}$; i … interest rate, P … depreciation period.

T … Annual full-load hours
C_{Fuel} … Primary fuel costs
η_{el} … Electric efficiency
$C_{O\&M}$ … Operation and maintenance costs
C_{Cert} … CO_2-certificate price
E_{CO2} … Specific CO_2-emissions

This formula incorporates fixed (i.e. investment) and variable / running costs (i.e. primary fuel costs and CO_2 emissions) of a new thermal power plant. Electricity generation costs of three different thermal power plant technologies were compared: Combined-Cycle Gas Turbines (CCGT), lignite and coal-fired power plants. The parameter settings for the different types of thermal power plants are given in Appendix 3.

To show the dependency of the economic analysis on CO_2 prices, annual full-load hours and natural gas prices, break-even points of the different thermal power plant technologies were calculated by varying these three parameters. For illustration, the economic borderlines between the different technologies are plotted together with the (mirrored) coverage of the residual load-figure (cf. Figure 7) in order to be able to indicate the maximum full-load hours available in the competitive area of the region.

In order to determine the influence of the CO_2 price on the economic trade-off between the three different thermal power plant technologies, the CO_2-certificate price is plotted on the vertical axis of the diagram. The natural gas price is set as a varying parameter in the different analyses / diagrams[18].

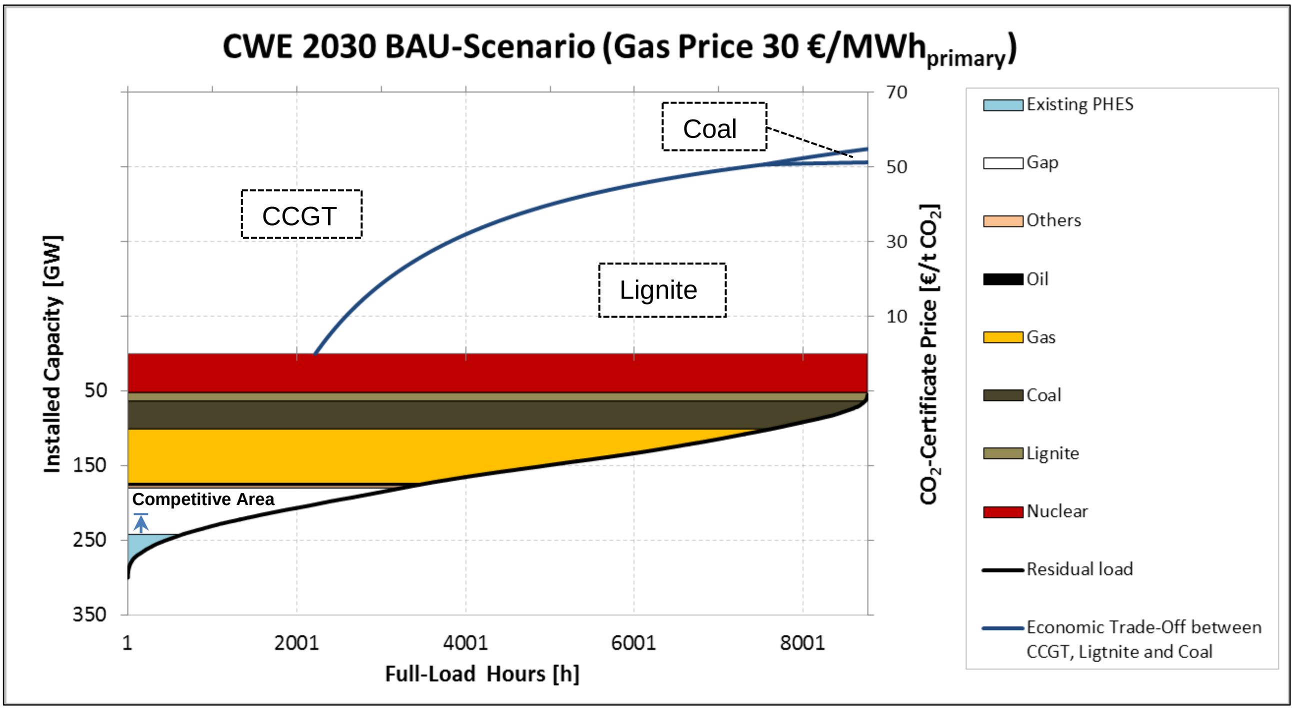


Figure 8: Economic trade-offs between the different types of new thermal power plants to fill the missing generation gap in the CWE region in the year 2030 (Source: EEG)

---

[18] More information explaining this approach in detail can be found in Körbler et al. (2011).

As an example, Figure 8 shows the economic trade-offs between the three different types of new thermal power plants to fill the missing generation gap in the CWE region in the year 2030 (BAU scenario) for a gas price of 30 €/MWh$_{primary}$. It can be seen that the competitive area reaches to a maximum of about 3000 annual full-load hours. This means that, depending on the CO_2-certificate price, only new lignite and CCGT power plants are economic within the competitive area for a given gas price. For a CO_2-certificate price above approximately 30 €/t CO_2, new CCGT power plants are the most economic generation technology type.

As already mentioned previously, the most economic new thermal power plant technology can be seen as a competitor / benchmark for new PHES power plants in the region.

3.3 Comparison of Selected Results of Different Regions in the BAU Scenario in the Year 2030

In the following subsections, selected results of the BAU scenario in the year 2030 are shown for the Iberian Peninsula, CEE and the Nordic region (the results of the CWE region were already shown in the previous section 3.2), showing the most interesting outcomes. The results of remaining European electricity market regions (including the age structure of the thermal power plant-portfolio) are shown in Appendix 4.

3.3.1 Iberian Peninsula (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 PHES in the BAU scenario for the Iberian Peninsula in the year 2030.

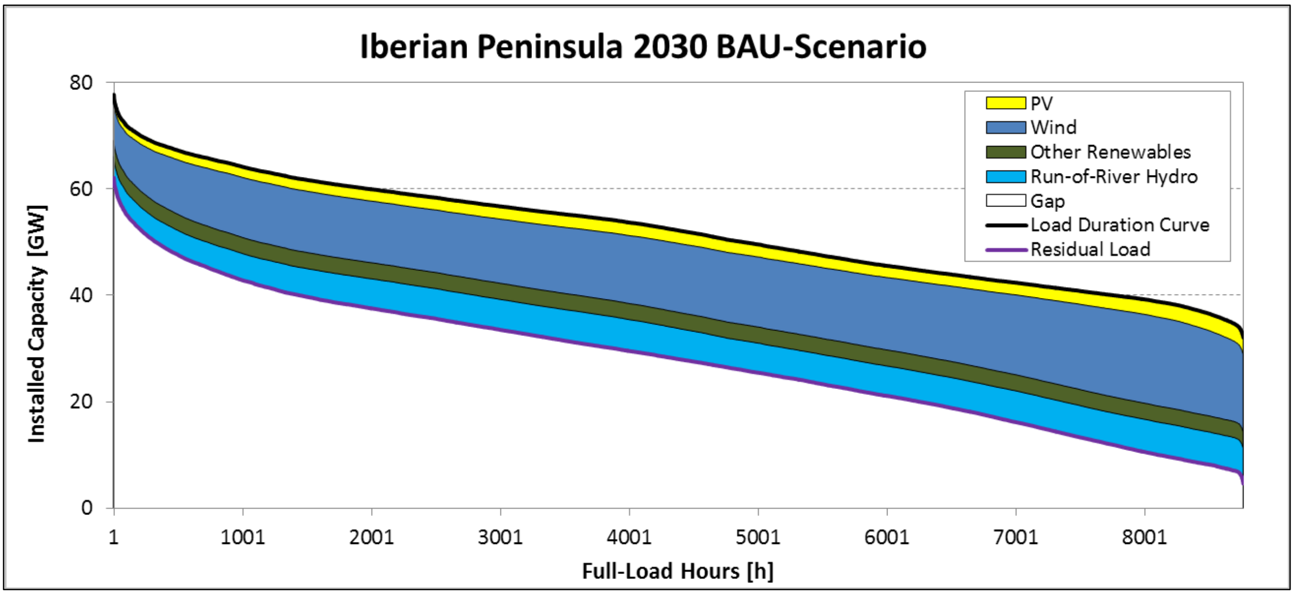


Figure 9: Load duration and residual load curve for the Iberian Peninsula in the BAU scenario in the year 2030 (Source: EEG)

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).

This set of flexible gas-fired electricity generation technologies (i.e. CCGT's and conventional open-cycle gas turbines (OCGT)[19]) 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. These gas-fired generation technology types 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, UK & 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.

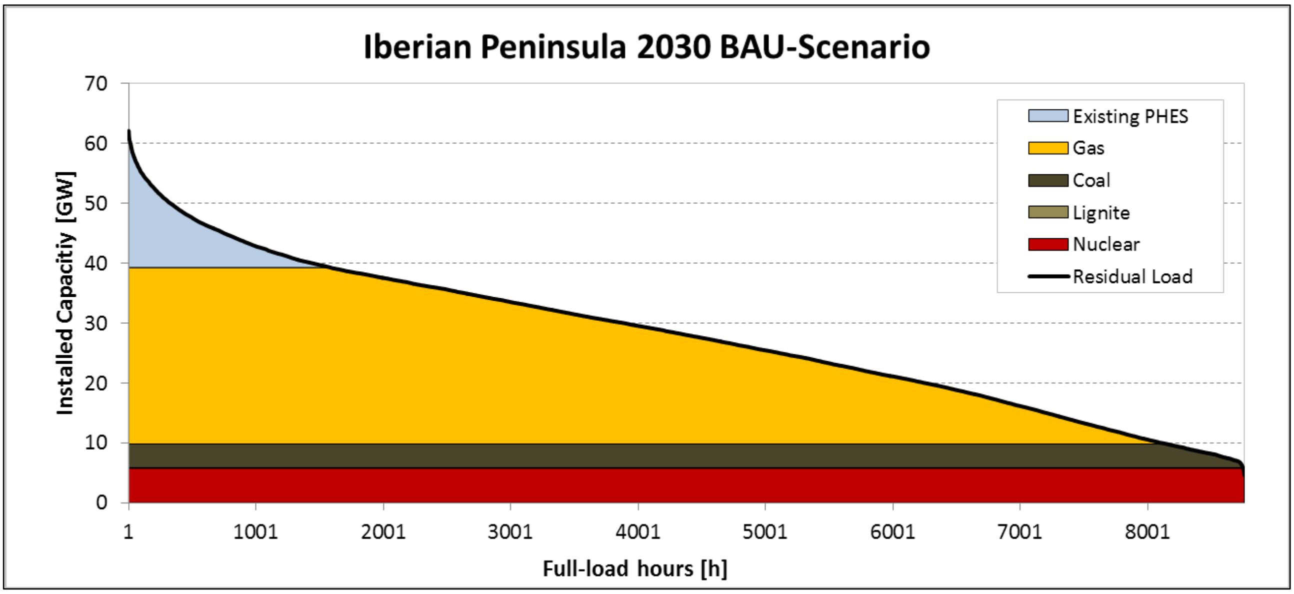


Figure 10: Coverage of the 2030 residual load of the Iberian Peninsula with existing thermal power plants and PHES in the BAU scenario (Source: EEG)

3.3.2 Central Eastern Europe (BAU scenario 2030)

The derivation of the residual load curve and its coverage with existing thermal power plants and PHES in the BAU scenario for the CEE region in the year 2030 is presented in Figure 11 and Figure 12. Due to low future RES-E deployment and only small amounts of still existing thermal power plants, a big gap of missing generation capacities already appears in the year 2030 in the BAU scenario. Additionally, only small volumes of PHES power plants and further PHES potentials are available in the region, leading to high investment needs in new thermal power plant units (and / or high electricity imports from neighbouring regions).

---

[19] See Deliverable 2.2 of the stoRE project for more details.

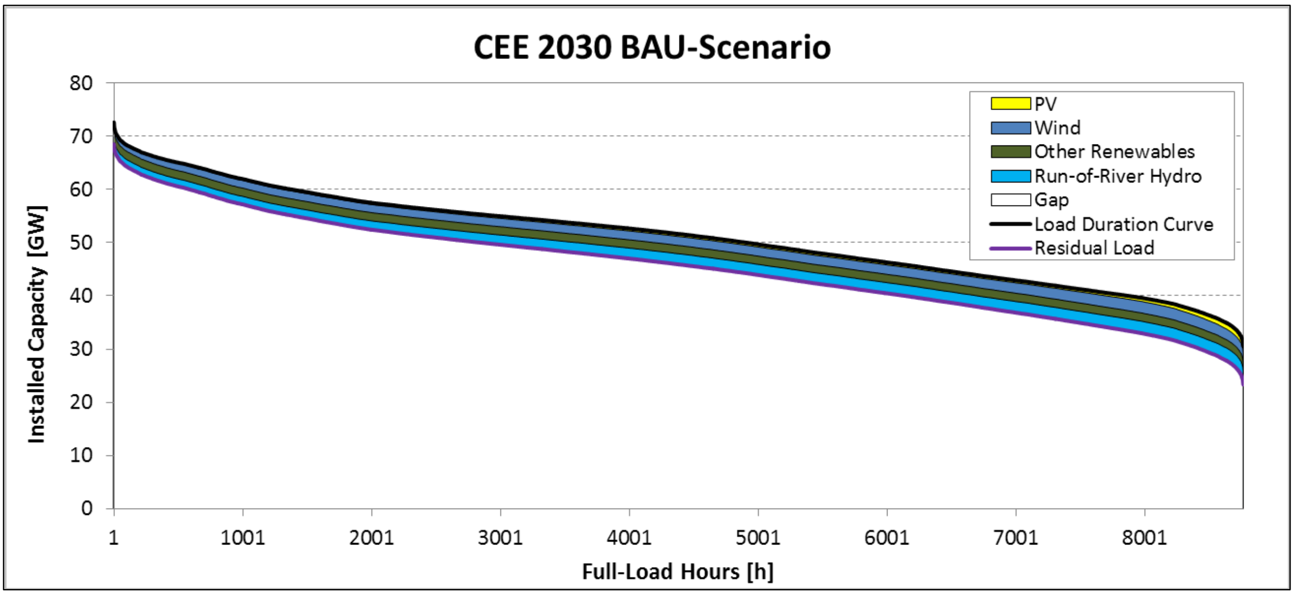


Figure 11: Load duration and residual load curve for the CEE region in the BAU scenario in the year 2030 (Source: EEG)

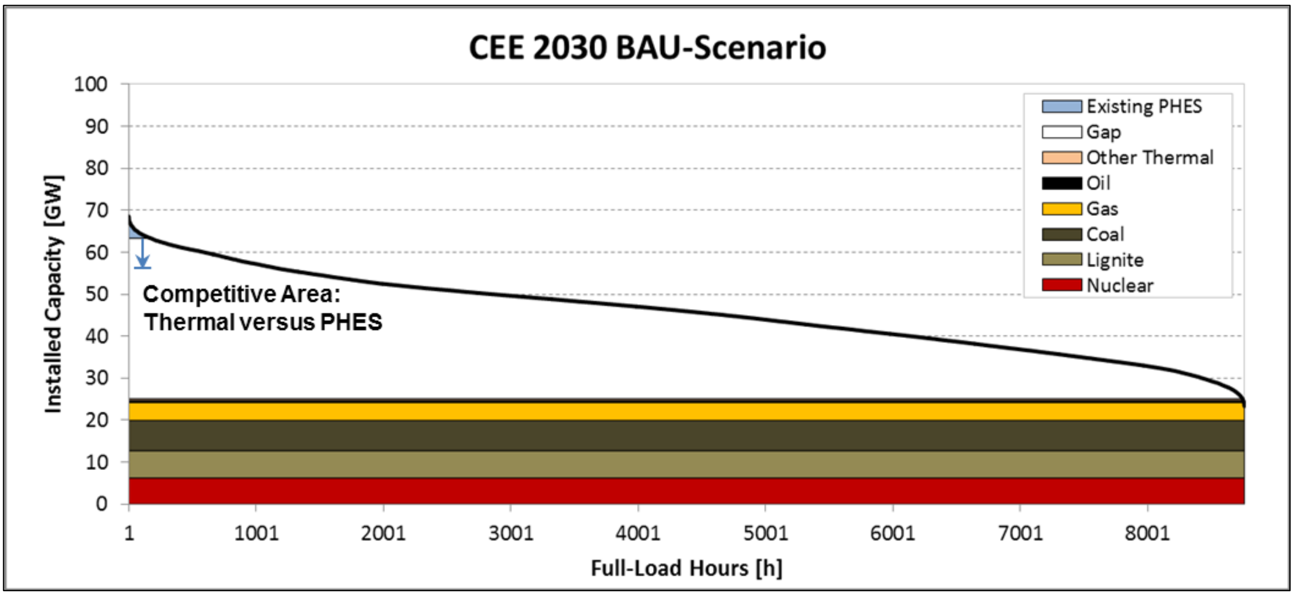


Figure 12: Coverage of the 2030 residual load of the CEE region with existing thermal power plants and PHES in the BAU scenario (Source: EEG)

3.3.3 Nordic Region (BAU scenario 2030)

Figure 13 and Figure 14 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. As previously mentioned, 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 14 as existing (P)HES. These existing (P)HES systems are capable to cover major parts of the residual load, but still leave a gap

Supported by INTELLIGENT ENERGY EUROPE

of missing generation capacity in the year 2030, which could partly be filled by new (P)HES schemes.

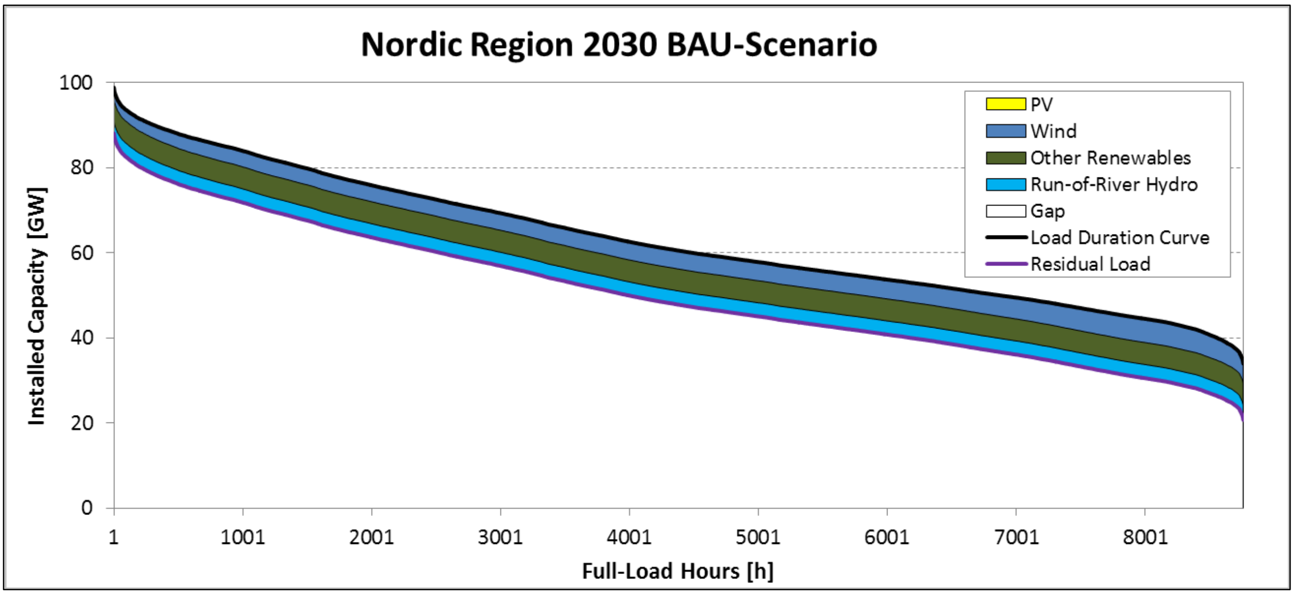


Figure 13: Load duration and residual load curve for the Nordic region in the BAU scenario in the year 2030 (Source: EEG)

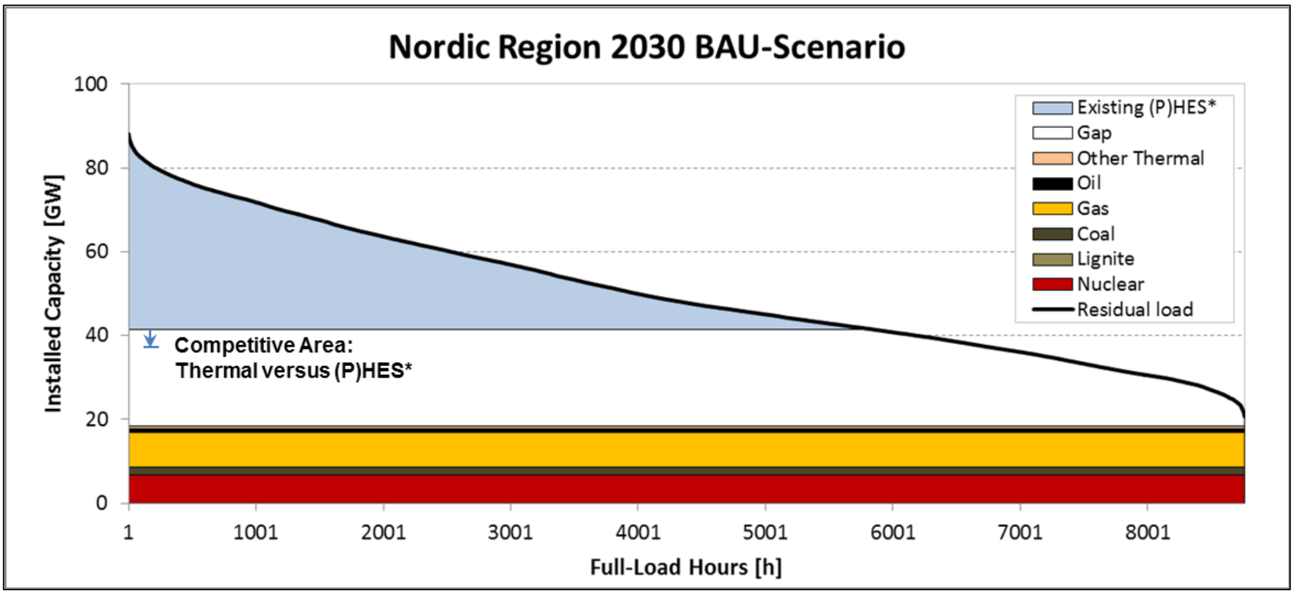


Figure 14: Coverage of the 2030 residual load of the Nordic region with existing thermal power plants and (P)HES in the BAU scenario (Source: EEG)

3.4 Comparison of Selected Results of Different Regions in the GREEN Scenario in the Year 2050

In the following subsections selected results of the GREEN scenario in the year 2050 are shown for the Iberian Peninsula, CWE, CEE and the Nordic region. The results of the remaining European regions (including the age structure of the thermal power plant-portfolio) are shown in Appendix 4.

3.4.1 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 15 and Figure 16). 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 generation capacities (gas and PHES power plants) are available in the system to cover the residual load.

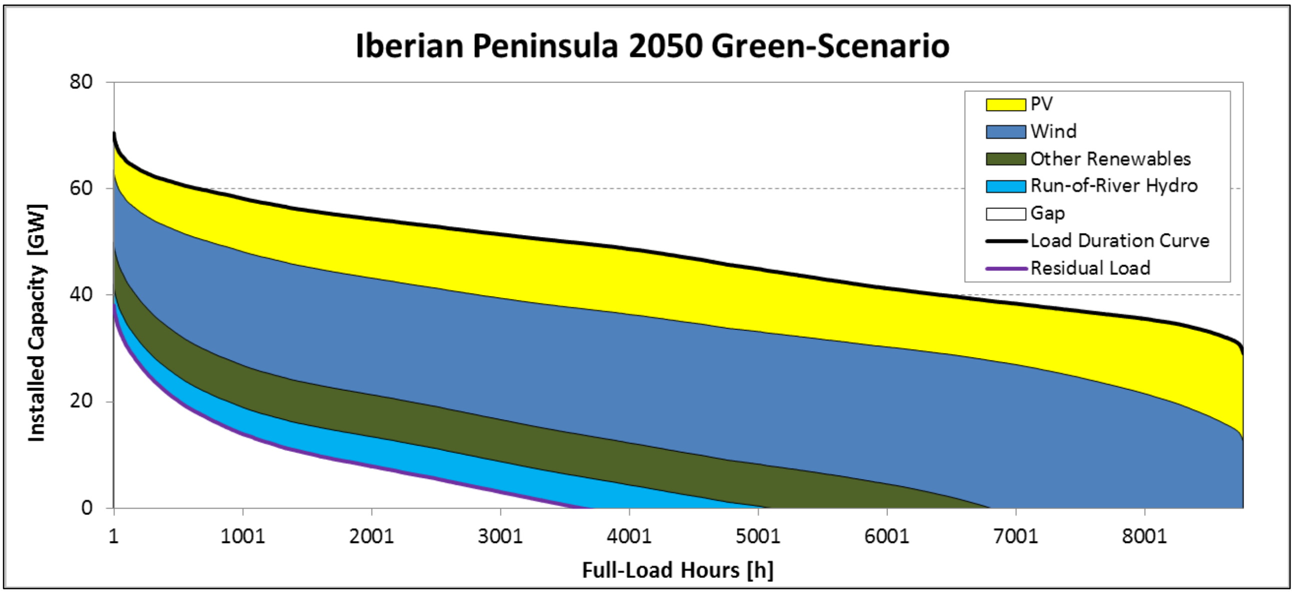


Figure 15: Load duration and residual load curve for the Iberian Peninsula in the GREEN scenario in the year 2050 (Source: EEG)

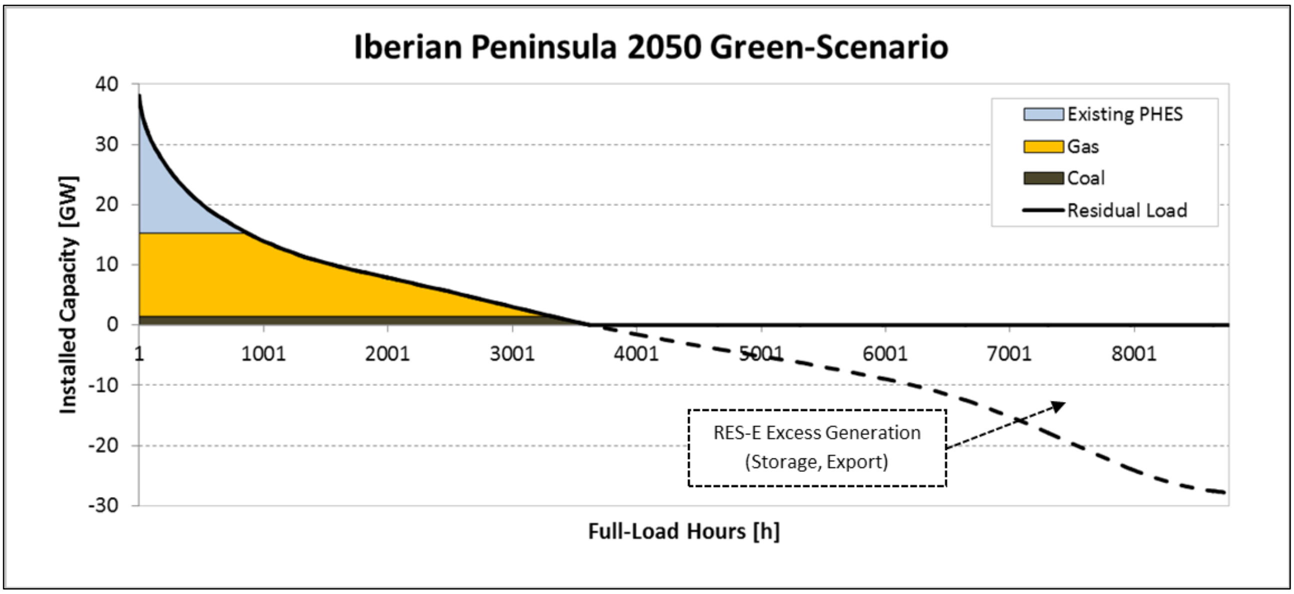


Figure 16: Coverage of the 2050 residual load of the Iberian Peninsula with existing thermal power plants and PHES in the GREEN scenario (Source: EEG)

Supported by INTELLIGENT ENERGY EUROPE

3.4.2 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 17 and Figure 18). Therefore, also in the CWE region PHES systems can help fully exploiting future RES-E generation (cf. section 3.4.1). 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.

Similar results can be observed in the SEE region (see Appendix 4).

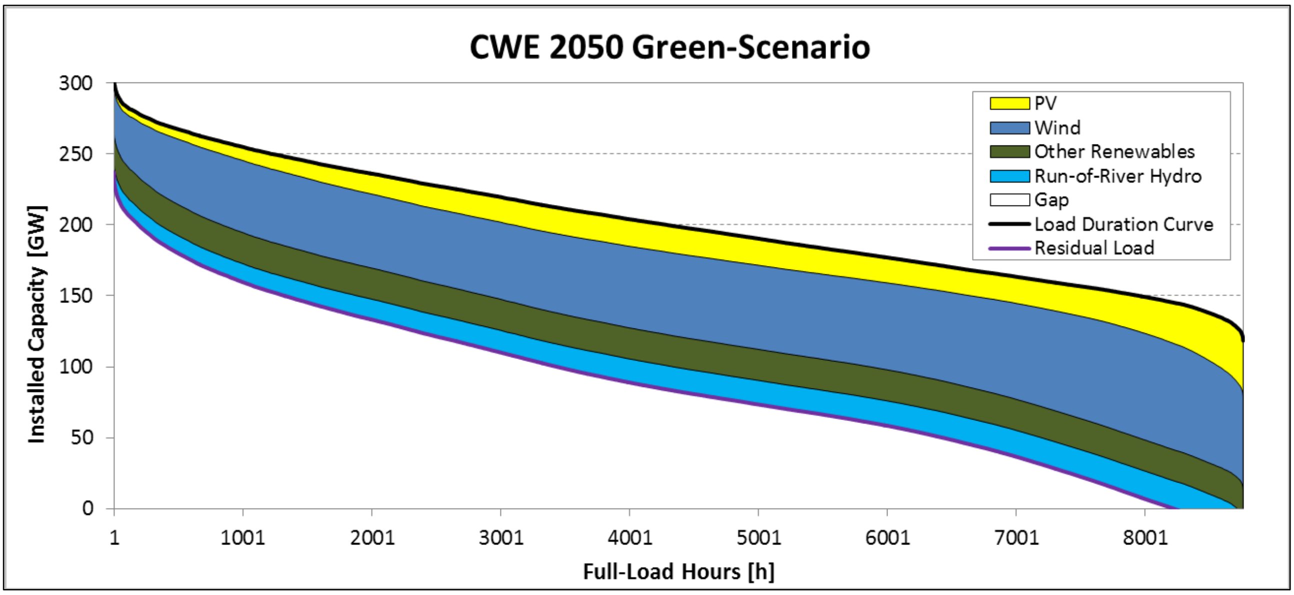


Figure 17: Load duration and residual load curve for the CWE region in the GREEN scenario in the year 2050 (Source: EEG)

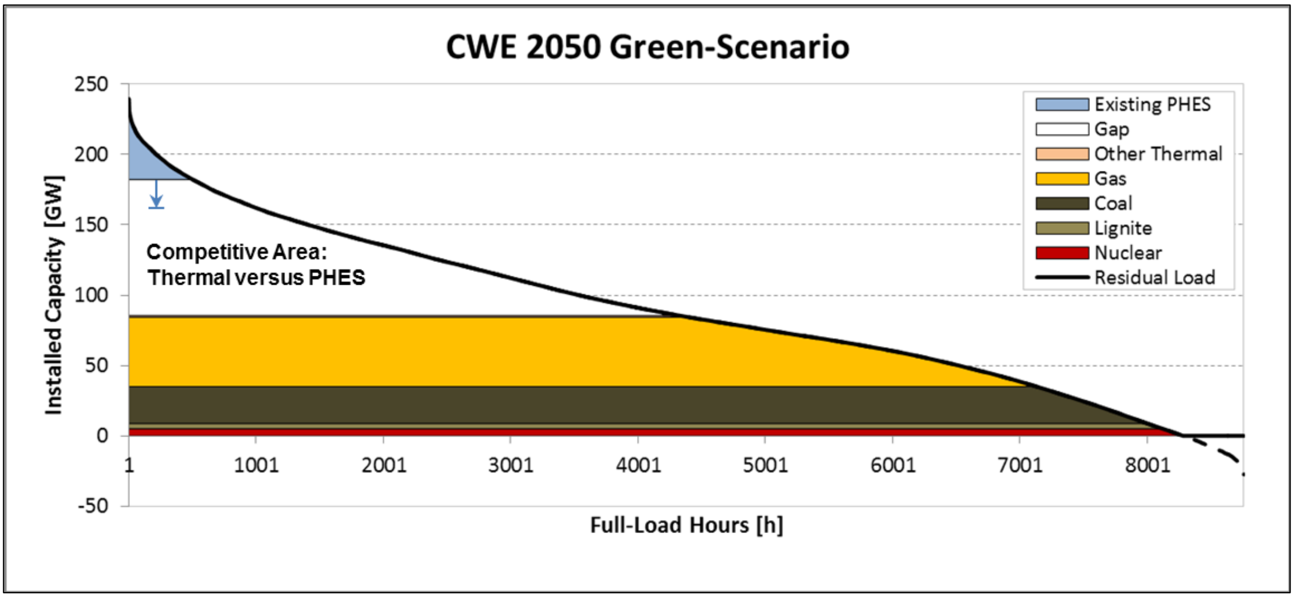


Figure 18: Coverage of the 2050 residual load of the CWE region with existing thermal power plants and PHES in the GREEN scenario (Source: EEG)

Supported by INTELLIGENT ENERGY EUROPE

3.4.3 Central Eastern Europe (GREEN scenario 2050)

As already indicated in the results of the BAU 2030 scenario, the CEE region is characterized by a high lack of electricity generation capacity in the year 2050 in the GREEN scenario, even though there is higher RES-E deployment (cf. Figure 19 and Figure 20). Due to the age structure of the power plant portfolio in the region, only very small amounts of the currently existing thermal power plants are available in the year 2050, i.e. new thermal power plants and / or PHES are badly needed.

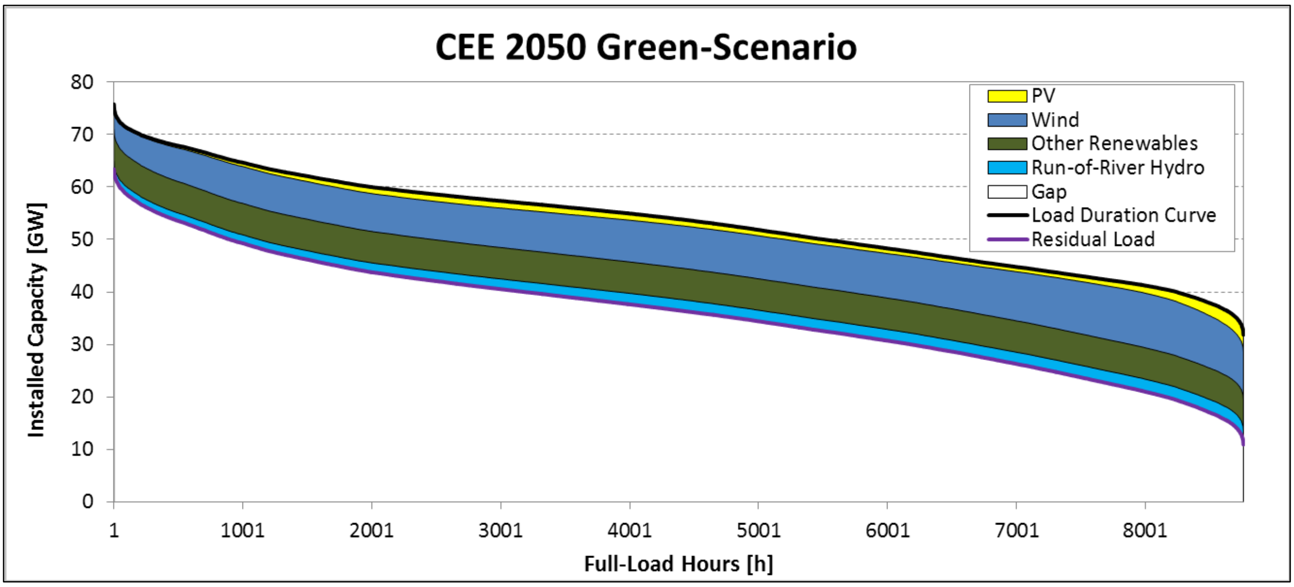


Figure 19: Load duration and residual load curve for the CEE region in the GREEN scenario in the year 2050 (Source: EEG)

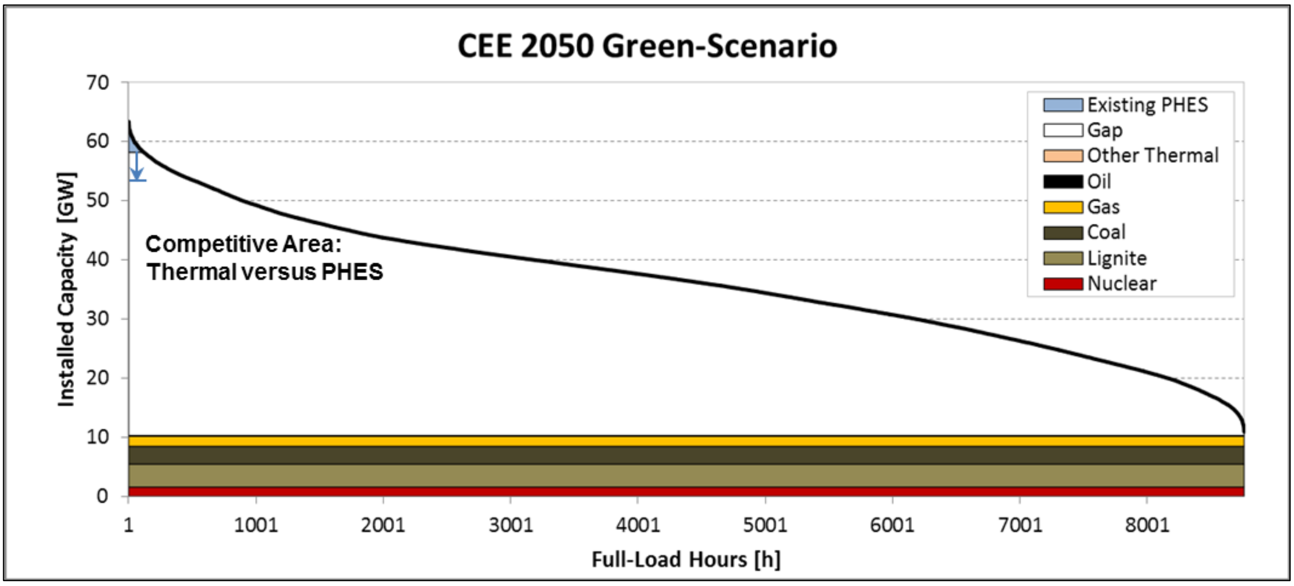


Figure 20: Coverage of the 2050 residual load of the CEE region with existing thermal power plants and PHES in the GREEN scenario (Source: EEG)

3.4.4 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 21 and Figure 22). About one fourth of this gap could be filled with new (P)HES schemes.

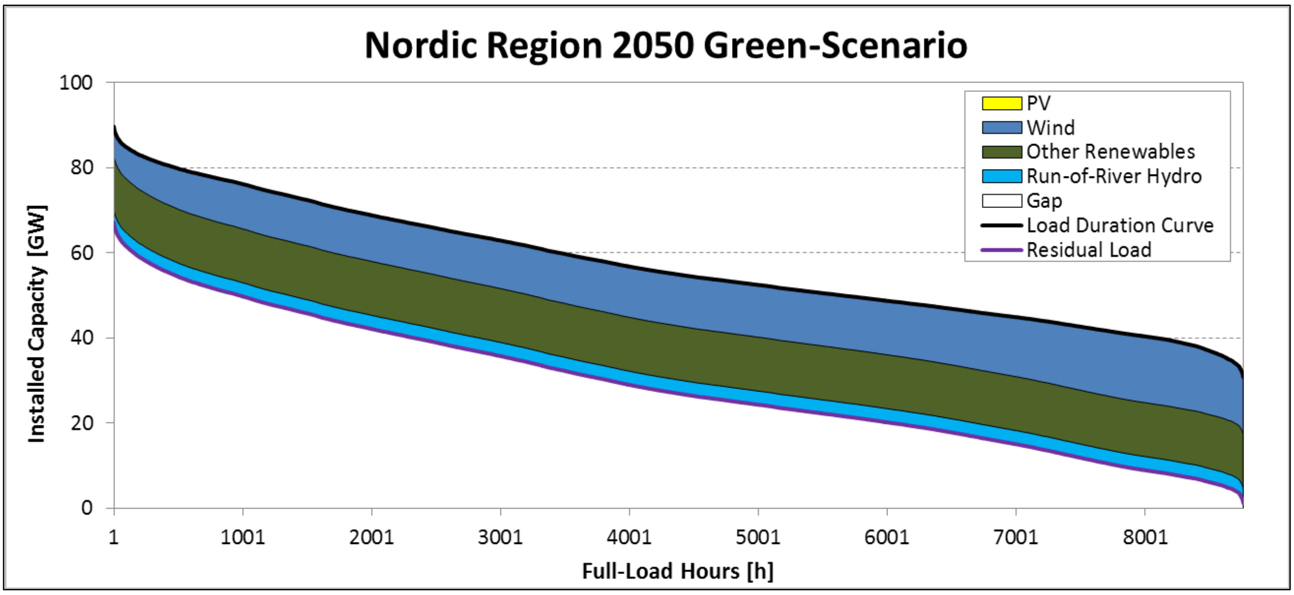


Figure 21: Load duration and residual load curve for the Nordic region in the GREEN scenario in the year 2050 (Source: EEG)

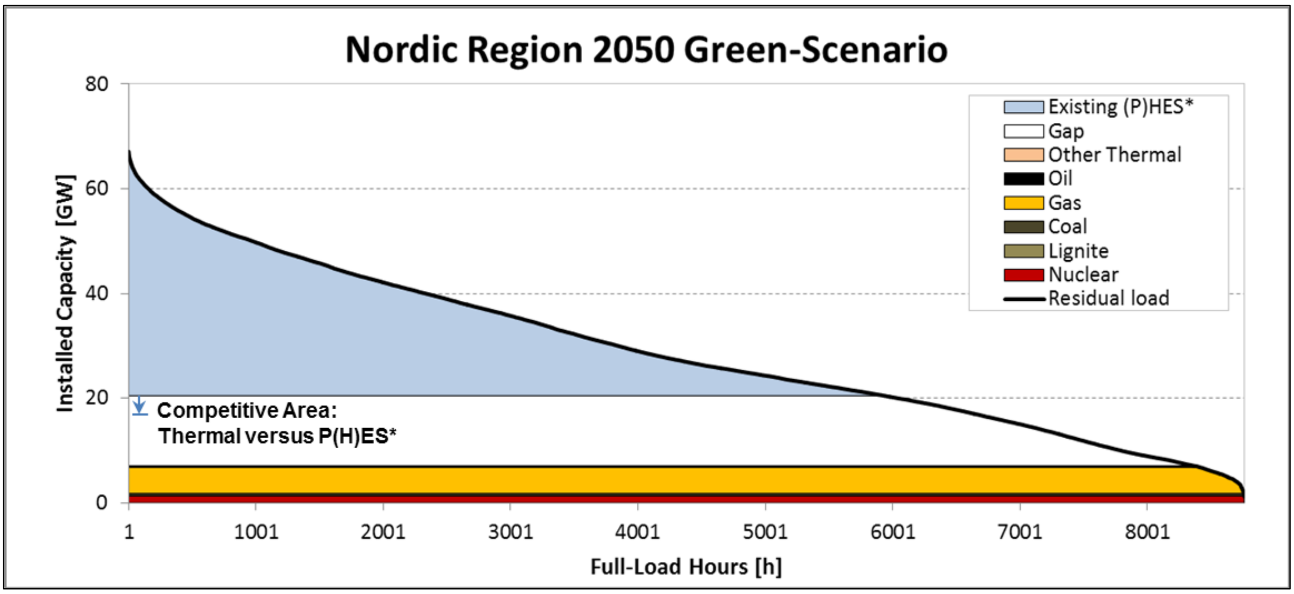


Figure 22: Coverage of the 2050 residual load of the Nordic region with existing thermal power plants and PHES in the GREEN scenario (Source: EEG)

Supported by INTELLIGENT ENERGY EUROPE

3.5 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, CEE, Nordic and the Iberian Peninsula. The result tables for remaining regions can be found in Appendix 4.

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. In the UK & Ireland region PHES systems will have a little contribution to the electricity system only, because of low future PHES potentials in comparison to the overall electricity demand / generation in the region.

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.

The CEE region is very similar to the CWE region in terms of possible contribution to neighbouring electricity regions, as it also has only limited capability. The region could profit from Nordic, SEE and Western Balkan PHES capacities in case of a negative correlation of wind.

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.

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)

Contribution of Transmission Expansion for Mitigation of Wind within the Regions and Management of Extreme Weather Events

	Within the Region		**Contributions from Outside ("Imports")**		**Contributions to other Regions ("Exports")**	
CEE	*Contribution in **CEE***		*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)	Limited	Limited (Anticorrelation Wind)
	High (New)	High (New)		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	Limited (Anticorrelation Wind)
				Limited (Correlation Wind)		Limited (Correlation Wind)
			*Transmission Expansion to **SEE***		*Transmission Expansion to **SEE***	
			Moderate	**Significant**	**Moderate**	**Significant**
			Limited	High (Anticorrelation Wind, PHES)	Limited	Limited (Anticorrelation Wind)
				Limited (Correlation Wind)		Limited (Correlation Wind)
			*Transmission Expansion to the **Western Balkan***		*Transmission Expansion to the **Western Balkan***	
			Moderate	**Significant**	**Moderate**	**Significant**
			Limited	High (Anticorrelation Wind, PHES)	Limited	Limited (Anticorrelation Wind)
				Limited (Correlation Wind)		Limited (Correlation Wind)
			*Transmission Expansion to **CWE***		*Transmission Expansion to **CWE***	
			Moderate	**Significant**	**Moderate**	**Significant**
			Low	Low (Anticorrelation Wind)	Limited	Limited (Anticorrelation Wind)
				Low (Correlation Wind)		Limited (Correlation Wind)

Contribution of Transmission Expansion for Mitigation of Wind within the Regions and Management of Extreme Weather Events

	Within the Region		Contributions from Outside ("Imports")		Contributions to other Regions ("Exports")	
Nordic Region	*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)

4 Conclusions / Outlook

This report provides an overview on the possible contribution of bulk EST in future European electricity systems facilitating large-scale expansion of RES-E generation.

Initially, the geographic allocation of future potentials of bulk EST and future large-scale wind deployment in Europe were identified. The estimation of the future potential of bulk EST implementation is based on a review and synthesis of the most relevant existing work, studies and modelling results on this topic (on country level as well as on European level). Future European wind deployment scenarios were generated based on modelling results derived from the Green-X RES-E deployment simulation tool. The highest potentials for (P)HES in Europe are located in Scandinavia (especially Norway), in the Alps and Pyrenees. Two different future European RES-E deployment scenarios were generated: A business-as-usual scenario (BAU) with moderate increase of RES-E deployment and an environmental friendly scenario (GREEN) with high increase of RES-E deployment in Europe. Especially Germany, Spain, the United Kingdom and France are expected to have very high installed wind capacities in the year 2050, whereas most Balkan & Baltic countries only show low future wind deployment in both scenarios.

The analysis conducted in this report has focussed on the possible direct benefits and the possible future contribution of bulk EST implementation to balance an incumbent regional electricity system. This means that 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 was presented. Selected results for the years 2030 (BAU scenario) and 2050 (GREEN scenario) were also shown.

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.

Supported by INTELLIGENT ENERGY EUROPE

5 References

Beurskens et al: “Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States”, ECN-E--10-069, downloadable at http://www.ecn.nl/docs/library/report/2010/e10069.pdf, 2011

BMU: “Weiterentwicklung der Ausbaustrategie Erneuerbare Energien - Leistudie 2008“, downloadable at www.bmu.de/files/pdfs/allgemein/application/pdf/leitstudie2008.pdf, 2008

ENTSO-E: “Pilot Ten-Year Network Development Plan (TYNDP)”, Executive Summary 2010, downloadable at https://www.entsoe.eu/fileadmin/user_upload/_library/SDC/TYNDP/100630_TYNDP_Executive_Summary.pdf, 2010a

ENTSO-E: “System Adequacy Forecast 2010 – 2025”, report and scenarios, downloadable at https://www.entsoe.eu/resources/publications/system-development/ , 2010b

ENTSO-E: Consumption Data, available at https://www.entsoe.eu/resources/data-portal/consumption/, 2012

EURELECTRIC: “Hydro in Europe: Powering Renewables”, full report, downloadable at: http://www.eurelectric.org , 2011

European Commission (EC): “Energy infrastructure priorities for 2020 and beyond - A Blueprint for an integrated European energy network”, Communication from the Commission - COM(2010) 677/4, downloadable at http://www.energy.eu/directives/com-2010-0677_en.pdf, 2010

European Commission (EC): “Priority Interconnection Plan”, Communication from the Commission - COM(2006) 846 final/2, downloadable at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0846:REV1:EN:PDF, 2007

Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES): “ Dynamische Simulation der Stromversorgung in Deutschland nach dem Ausbauszenario der Erneuerbaren-Energien-Branche“, final report, downloadable at http://www.bee-ev.de/_downloads/publikationen/studien/2010/100119_BEE_IWES-Simulation_Stromversorgung2020_Endbericht.pdf, 2009

Gatzen: “The Economics of Power Storage – Theory and Empirical Analysis for Central Europe”, Schriften des Energiewirtschaftlichen Instituts Band 63, Oldenburg Industrieverlag, ISBN 978-3-8356-3138-0, 2008

Huber et al: “Action plan for a dynamic RES-E policy”, Report of the European research project Green-X – funded by the EC-DG Research, Vienna University of Technology, 2004

Intergovernmental Panel on Climate Change (IPCC): “Renewable Energy Sources and Climate Change Mitigation”, IPCC Special Report, prepared by Working Group III of the IPCC, 2011

International Energy Agency (IEA): “CO_2 Emissions from Fuel Combustion – Highlights”, 2011 Edition, downloadable at: www.iea.org/co2highlights/co2highlights.pdf, 2011

Joint Research Centre (JRC): “Pumped-hydro energy storage: potential for transformation from single dams”, JRC Scientific and Technical Report, ISBN 978-92-79-23182-7, downloadable at: http://setis.ec.europa.eu/newsroom-items-folder/report-pumped-hydro-energy-storage-potential-for-transformation-from-single-dams, 2012

Körbler et al: “Zukünftige Wirtschaftlichkeitsgrenzen fossiler Kraftwerkstechnologien im deutschen Strommarkt mit einem hohen Anteil erneuerbarer Stromerzeugung“, Diploma Thesis, Vienna University of Technology, 2011

Pfaffenberger et al: “Investitionen im liberalisierten Energiemarkt: Optionen, Marktmechanismen, Rahmenbedingungen", Bremer Energie Institut, final report, 2004

PLATTS: „Electric Power Plant Database – Europe“, www.platts.com, 2010

Solar Radiation Data (SoDa), website: http://www.soda-is.com, 2012

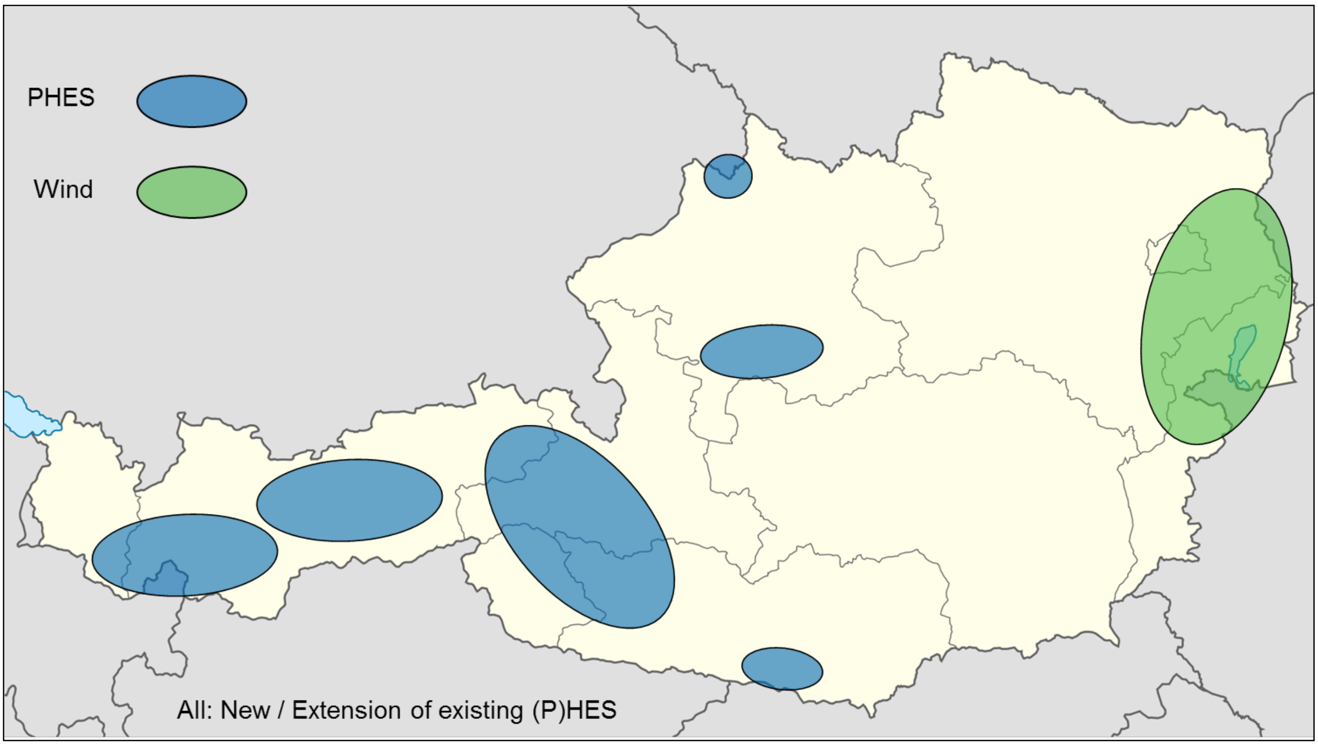
Sun et al: “Auswirkungen einer Laufzeitverlängerung deutscher Kernkraftwerke“, Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart, 2010

List of Figures

Appendix 1: Geographical Allocation of Future Bulk EST Potentials & Large-scale Wind Deployments within the Target Countries

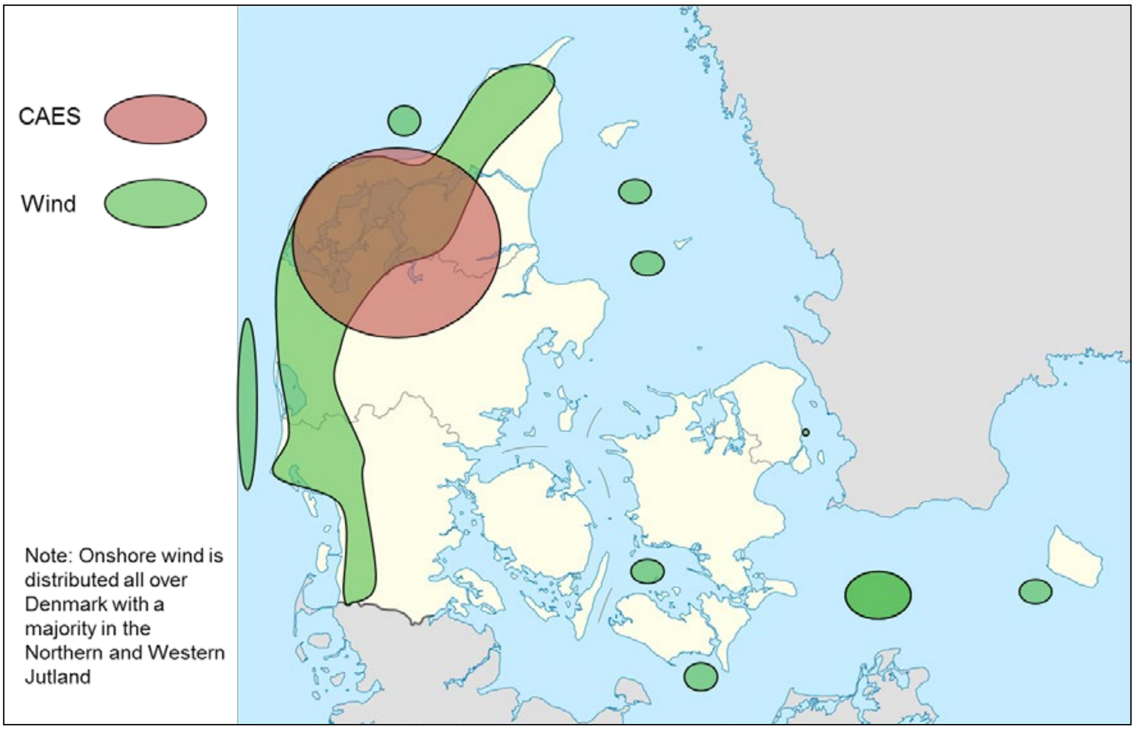
In the following sections of Appendix 1, the geographical allocation of bulk EST potentials and future centres of large-scale wind deployment within the six target countries of the stoRE project (Austria, Denmark, Germany, Greece, Ireland and Spain) is shown. The maps were edited by the respective project partners within the countries.

A1.1 Austria

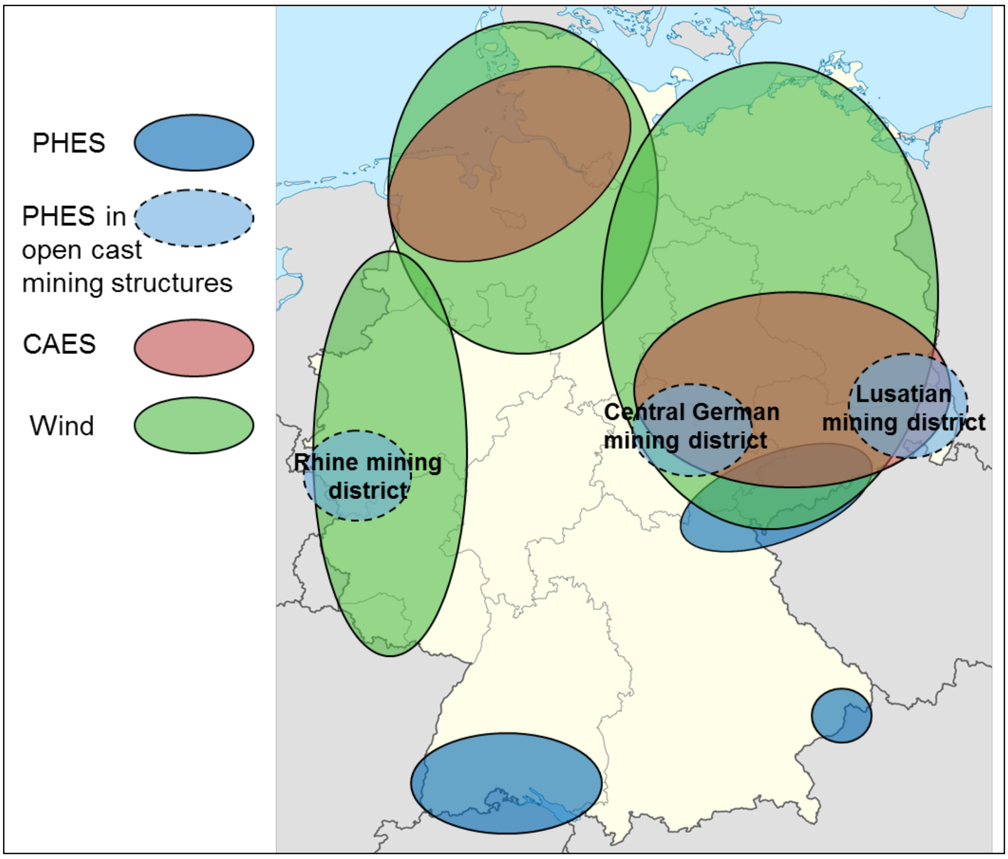


Supported by INTELLIGENT ENERGY EUROPE

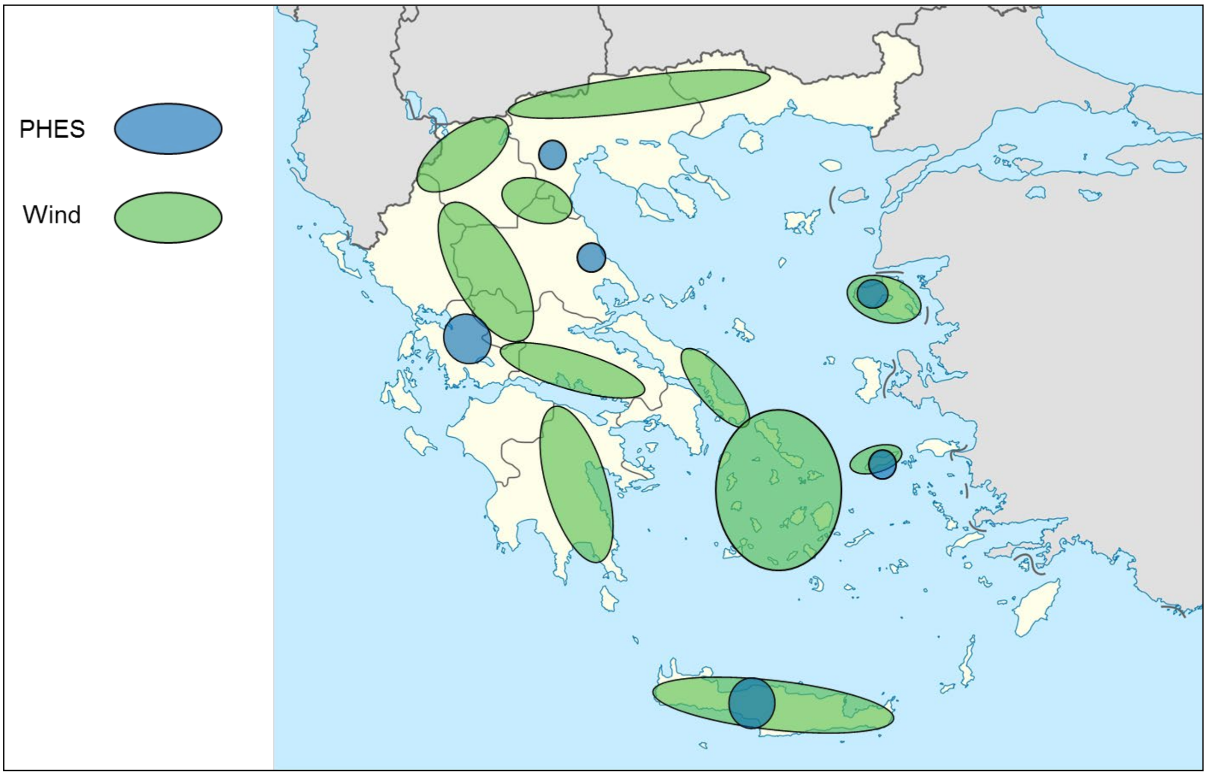
A1.2 Denmark



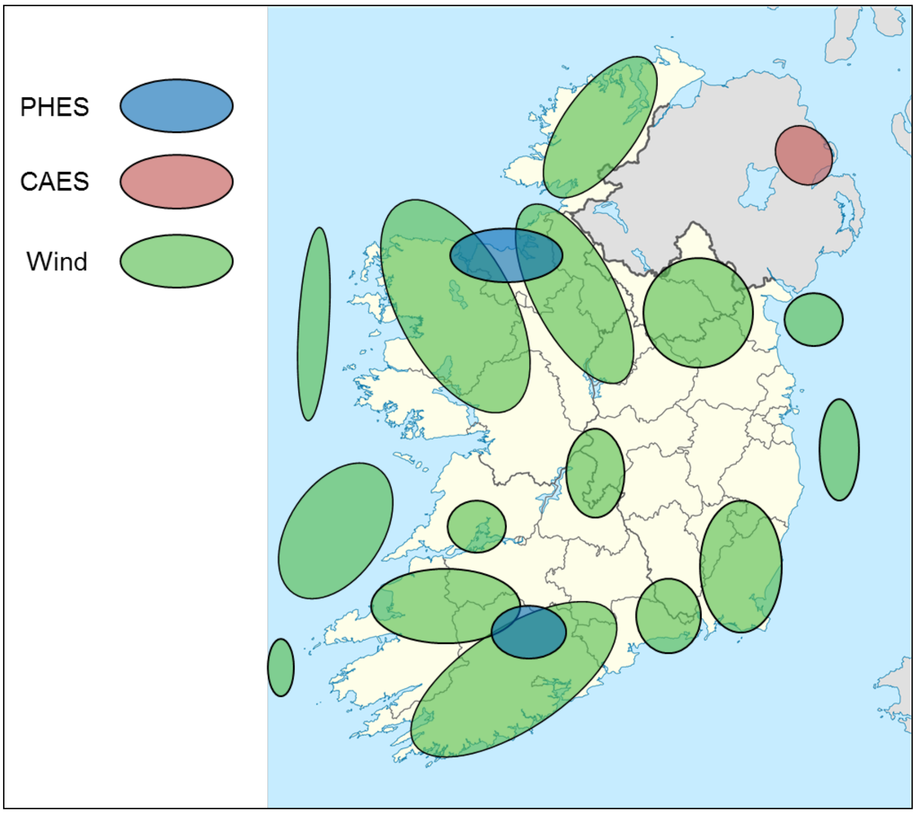
A1.3 Germany



A1.4 Greece

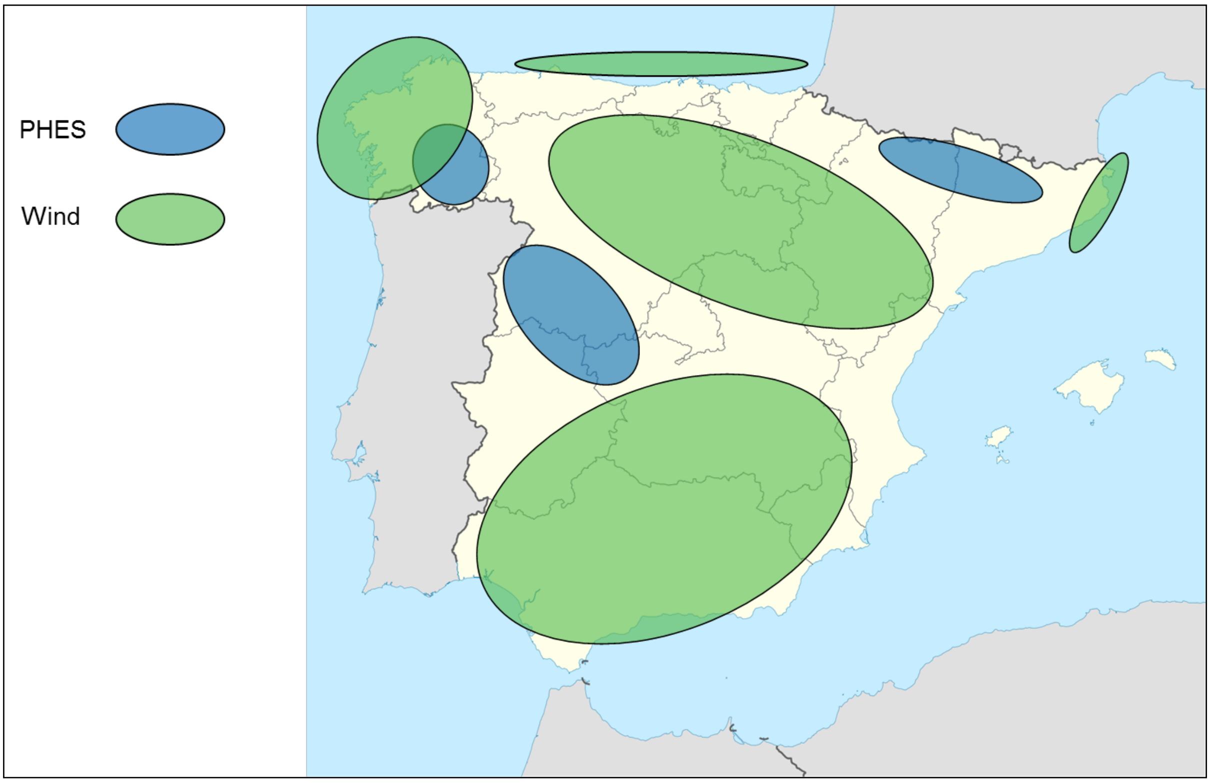


A1.5 Ireland



Supported by INTELLIGENT ENERGY EUROPE

A1.6 Spain



Supported by INTELLIGENT ENERGY EUROPE

Appendix 2: (P)HES Potential and Wind Deployment Data

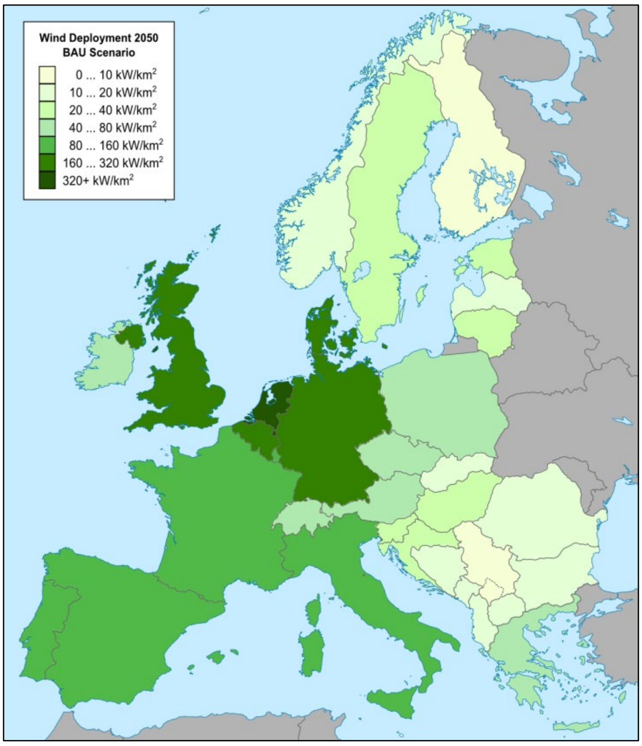
The following tables show the input data for Figure 1, Figure 2 and Figure 3 (section 2), i.e. (P)HES potential and wind deployment data for the BAU and GREEN scenario in the year 2050. The target countries of the stoRE project are highlighted in bold.

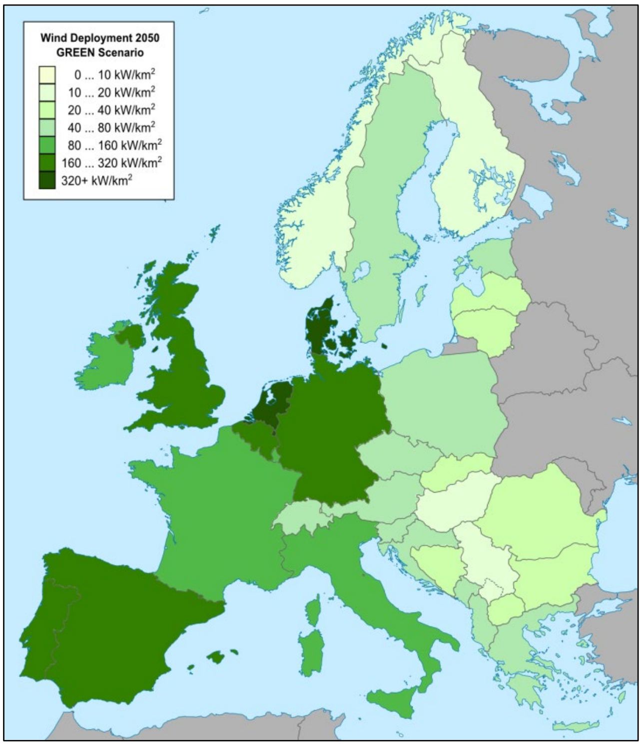
Country Data [MW]	(P)HES Potent.	Wind Deployment 2050	
		BAU	GREEN
Albania	0	450	1817
Austria	**12800**	**4240**	**4710**
Belgium	1300	6451	9207
Bosnia-Herzeg.	1520	923	1273
Bulgaria	2790	2084	3900
Croatia	1900	2110	3239
Czech Rep.	1900	5464	6172
Denmark	**0**	**10491**	**16568**
Estonia	500	1564	2053
Finland	0	1081	4185
France	19500	51563	61480
Germany	**12187**	**81419**	**93256**
Greece	**4809**	**7220**	**10061**
Hungary	6000	1700	2000
Ireland	**1322**	**5525**	**9871**
Italy	15600	26805	28700
Latvia	0	1063	1881
Lithuania	1600	2039	2557
Luxembourg	1300	244	320
Macedonia	1370	350	772
Montenegro	900	200	600
Netherlands	0	17197	25593
Norway	30000	5913	7365
Poland	1950	15707	21031
Portugal	5700	14025	16209
Romania	4550	3680	5500
Serbia	1300	580	1360
Slovakia	1330	769	1175
Slovenia	600	750	1300
Spain	**20200**	**60914**	**83665**
Sweden	16200	11188	21869
Switzerland	14400	1679	2608
UK	4088	51801	75144
TOTAL	**182216**	**397189**	**527441**

Regional Data [MW]	(P)HES Potent.	Wind Deployment 2050	
		BAU	GREEN
Baltic Region	2100	4666	6491
CEE	5780	23640	30378
CWE	61487	162793	197174
Iberian Peninsula	25900	74939	99874
Italy	15600	26805	28700
Nordic Region	46200	28673	49987
SEE	12149	12984	19461
UK & Ireland	5410	57326	85015
Western Balkan	7590	5363	10361
TOTAL	**182216**	**397189**	**527441**

Supported by INTELLIGENT ENERGY EUROPE

The following figures show the wind deployment in power capacity per land area per country [kW/km^2] for European countries in the two different scenarios (left BAU, right GREEN) in the year 2050. It can be seen, that Denmark and the Netherlands have the highest installed wind capacities in relation to their land area.





Appendix 3: Parameter Settings for the Economic Trade-Off Analysis of the Different Types of Thermal Power Plant Technologies

Parameter-Settings 2007		**Lignite**	**Coal**	**Gas**
Spec. CO_2-Emissions (E_{CO2})[20]	[t CO_2/MWh$_{primary}$]	0.396	0.342	0.198
Investment Costs (C_{Inv})[21]	[€/kW]	1175	1000	435
Fuel Costs (C_{Fuel})[22]	[€/MWh$_{primary}$]	4.53	8.33	variable
Electric Efficiency (η)[21]	[%]	45	47	59
O&M Costs ($C_{O\&M}$)	[€/kWyr]	34	45	17
Interest Rate (i)	[%]	8	8	8
Depreciation Period (P)	[yr]	20	20	20
Annuity Factor (α)	[1]	0.1019	0.1019	0.1019

Parameter-Settings 2020		**Lignite**	**Coal**	**Gas**
Spec. CO_2-Emissions (E_{CO2})	[t CO_2/MWh$_{primary}$]	0.396	0.342	0.198
Investment Costs (C_{Inv})	[€/kW]	1100	950	400
Fuel Costs (C_{Fuel})	[€/MWh$_{primary}$]	5	9.69	variable
Electric Efficiency (η)	[%]	46	49	60
O&M Costs ($C_{O\&M}$)	[€/kWyr]	34	45	17
Interest Rate (i)	[%]	8	8	8
Depreciation Period (P)	[yr]	20	20	20
Annuity Factor (α)	[1]	0.1019	0.1019	0.1019

Parameter-Settings 2030		**Lignite**	**Coal**	**Gas**
Spec. CO_2-Emissions (E_{CO2})	[t CO_2/MWh$_{primary}$]	0.396	0.342	0.198
Investment Costs (C_{Inv})	[€/kW]	1060	900	400
Fuel Costs (C_{Fuel})	[€/MWh$_{primary}$]	5.25	10.52	variable
Electric Efficiency (η)	[%]	46.5	50.5	61
O&M Costs ($C_{O\&M}$)	[€/kWyr]	34	45	17
Interest Rate (i)	[%]	8	8	8
Depreciation Period (P)	[yr]	20	20	20
Annuity Factor (α)	[1]	0.1019	0.1019	0.1019

Parameter-Settings 2050		**Lignite**	**Coal**	**Gas**
Spec. CO_2-Emissions (E_{CO2})	[t CO_2/MWh$_{primary}$]	0.396	0.342	0.198
Investment Costs (C_{Inv})	[€/kW]	1050	900	400
Fuel Costs (C_{Fuel})	[€/MWh$_{primary}$]	5.5	10.9	variable
Electric Efficiency (η)	[%]	47.5	52	62
O&M Costs ($C_{O\&M}$)	[€/kWyr]	34	45	17
Interest Rate (i)	[%]	8	8	8
Depreciation Period (P)	[yr]	20	20	20
Annuity Factor (α)	[1]	0.1019	0.1019	0.1019

---

[20] [IEA, 2011]

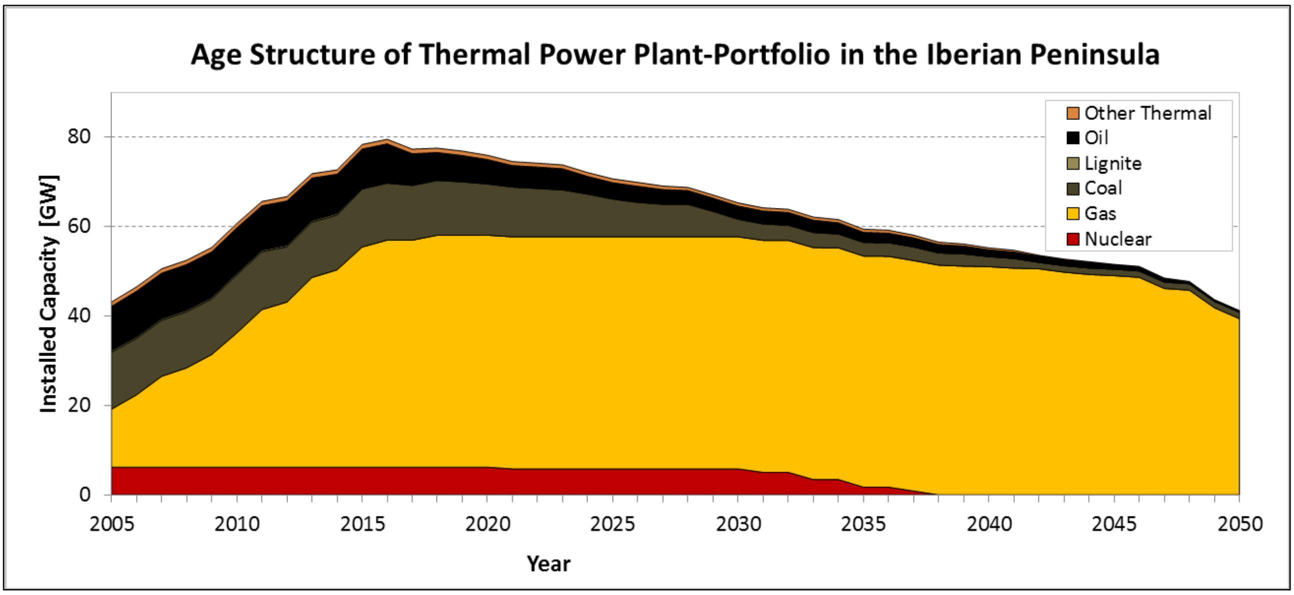
[21] [BMU, 2008]

[22] [BMU, 2009], [Pfaffenberger et al, 2004] and [Sun et al, 2010]

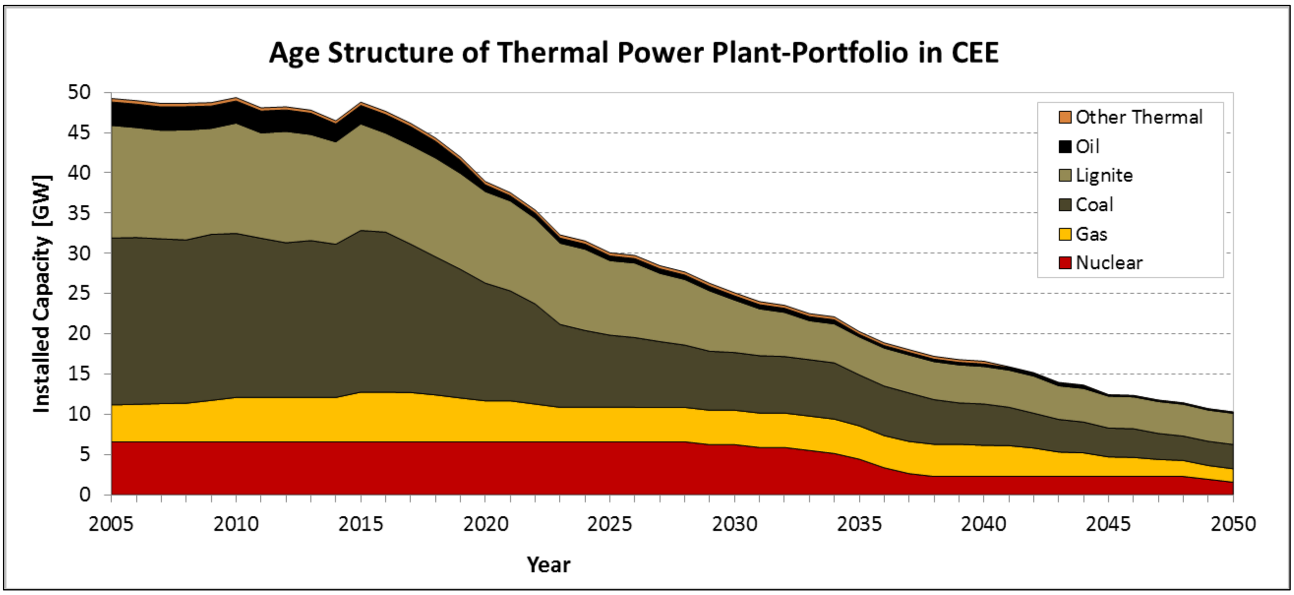
Appendix 4: Further Results

A4.1 Age Structure of the Thermal Power Plant-Portfolio

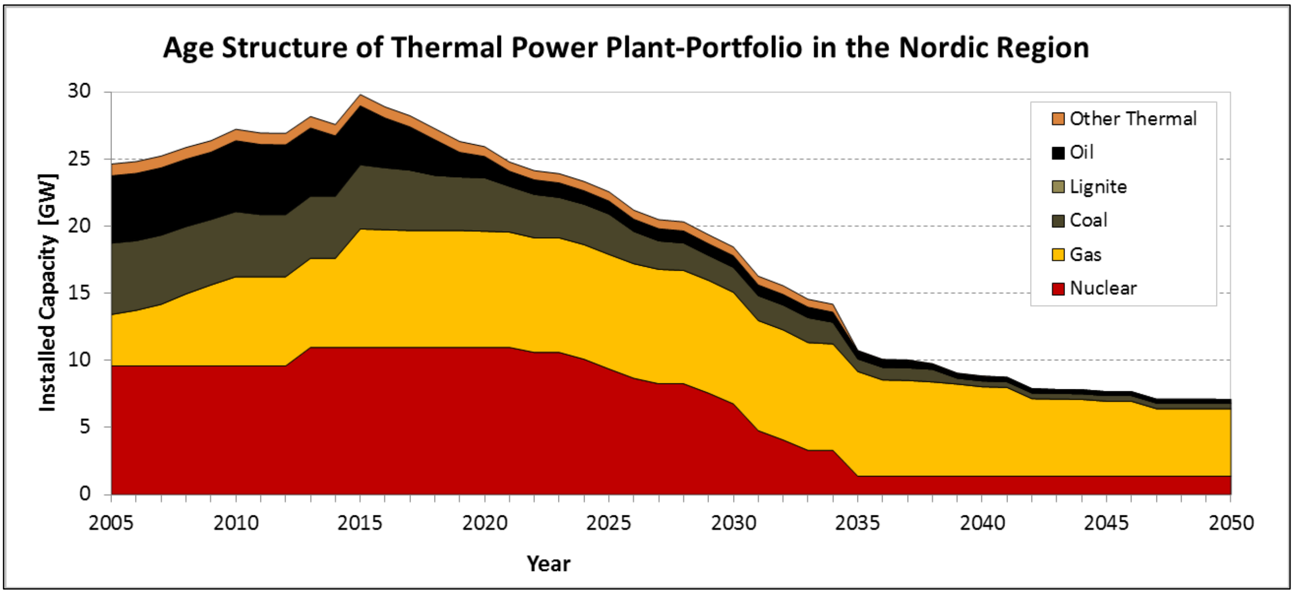
A4.1.1 Iberian Peninsula



A4.1.2 Central Eastern Europe



A4.1.3 Nordic Region

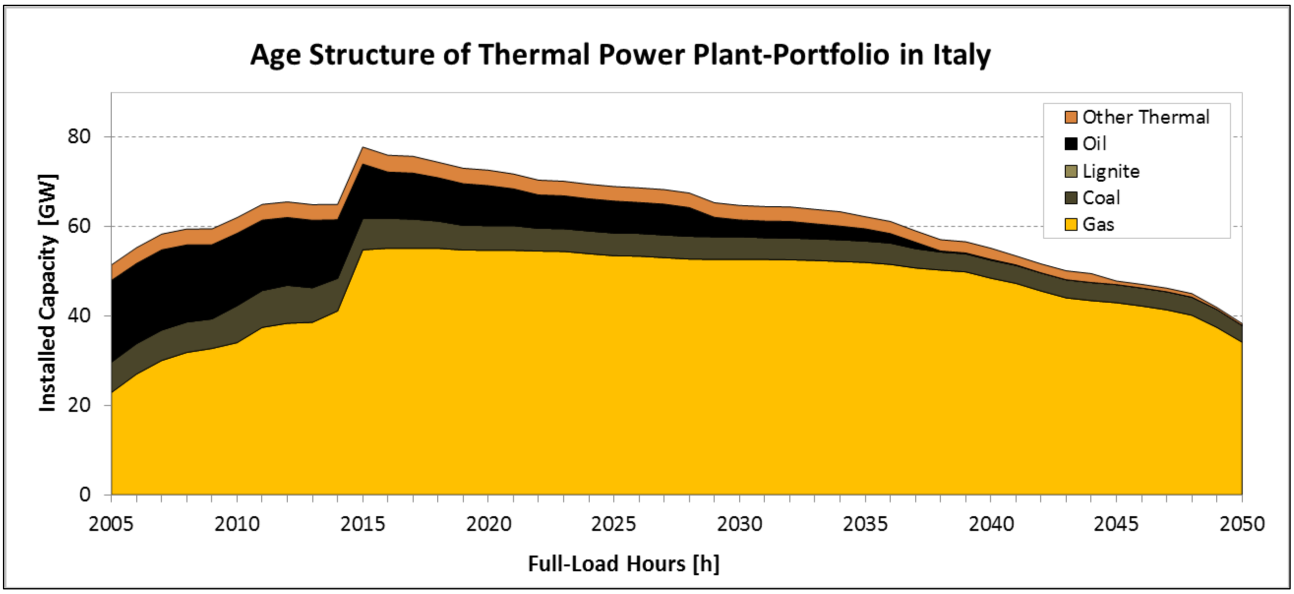


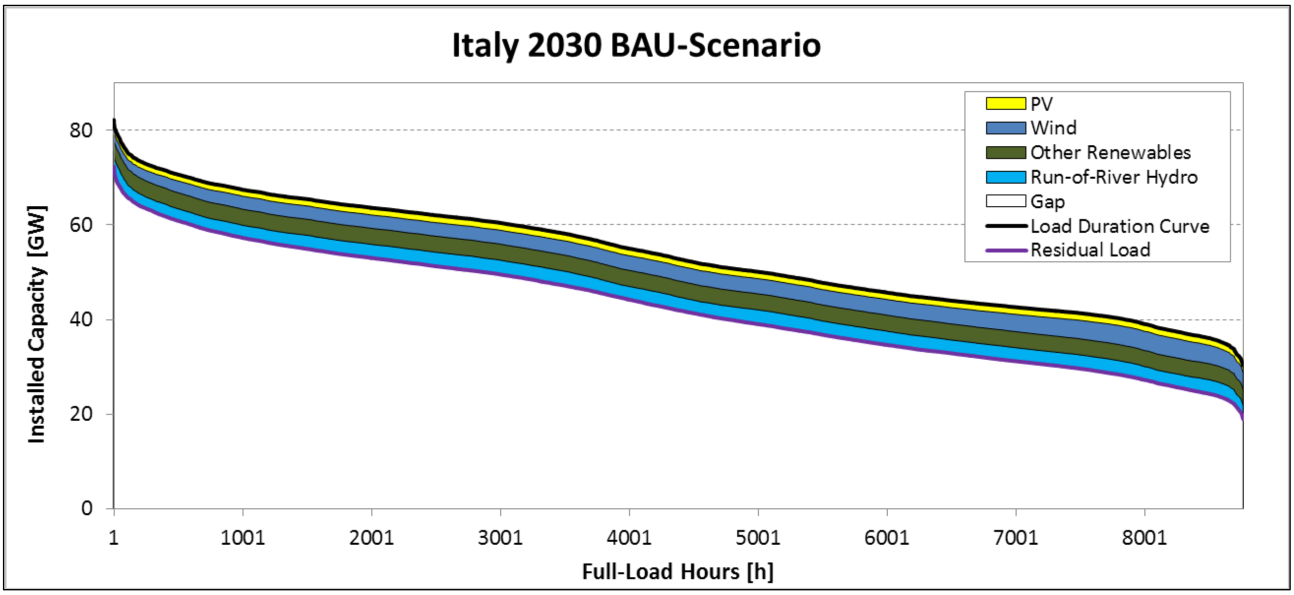
A4.2 Further Results of the BAU Scenario in the Year 2030

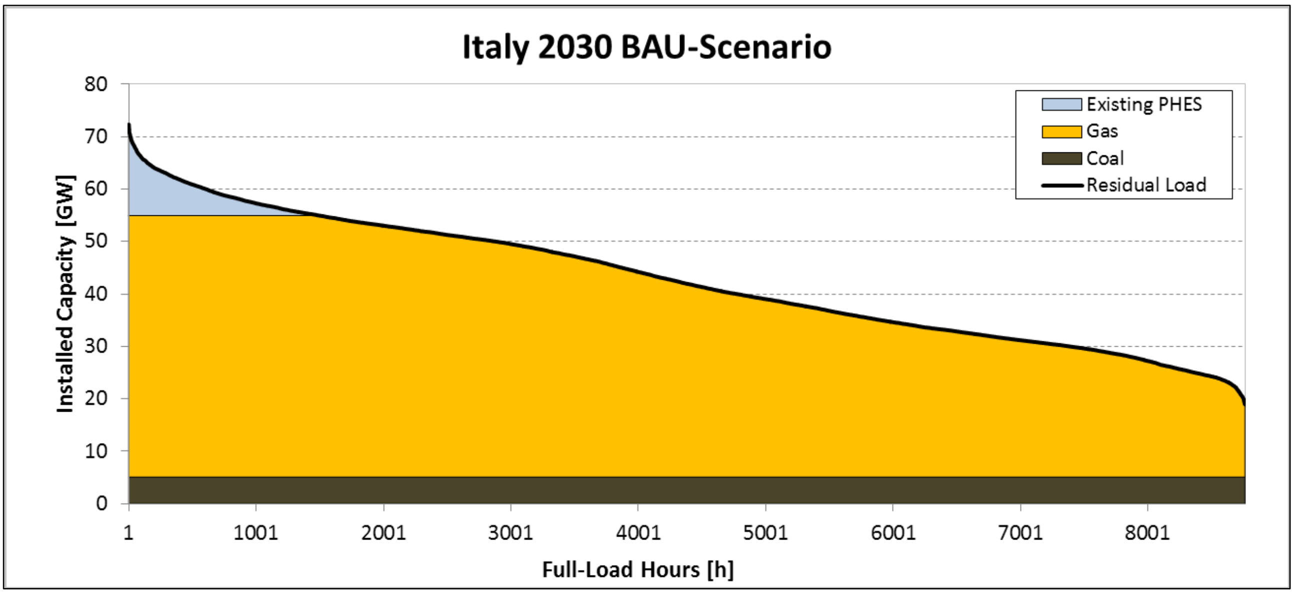
In the following sections selected results for the European electricity regions of Italy, Western Balkan, SEE, Baltic region and UK & Ireland are presented for the BAU scenario in the year 2030. For each region the age structure of the thermal power plant-portfolio, the load duration & residual load curve and the coverage of the residual load curve with existing thermal power plants and PHES are given (three figures per regions in total).

Supported by INTELLIGENT ENERGY EUROPE

A4.2.1 Italy (BAU scenario 2030)

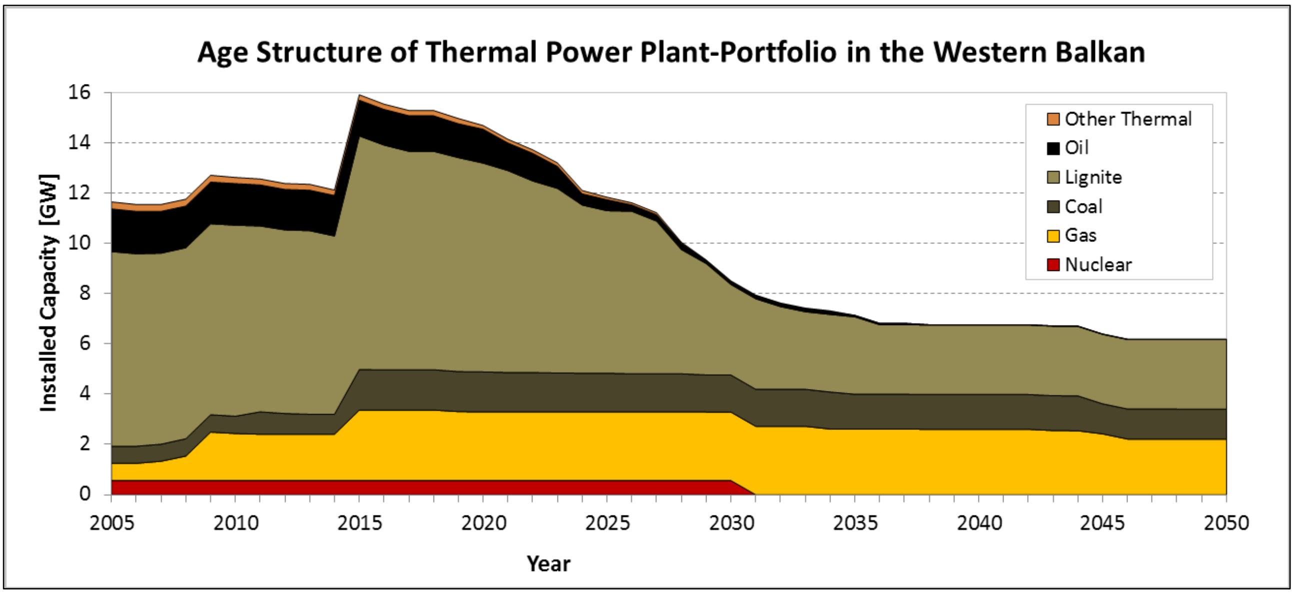


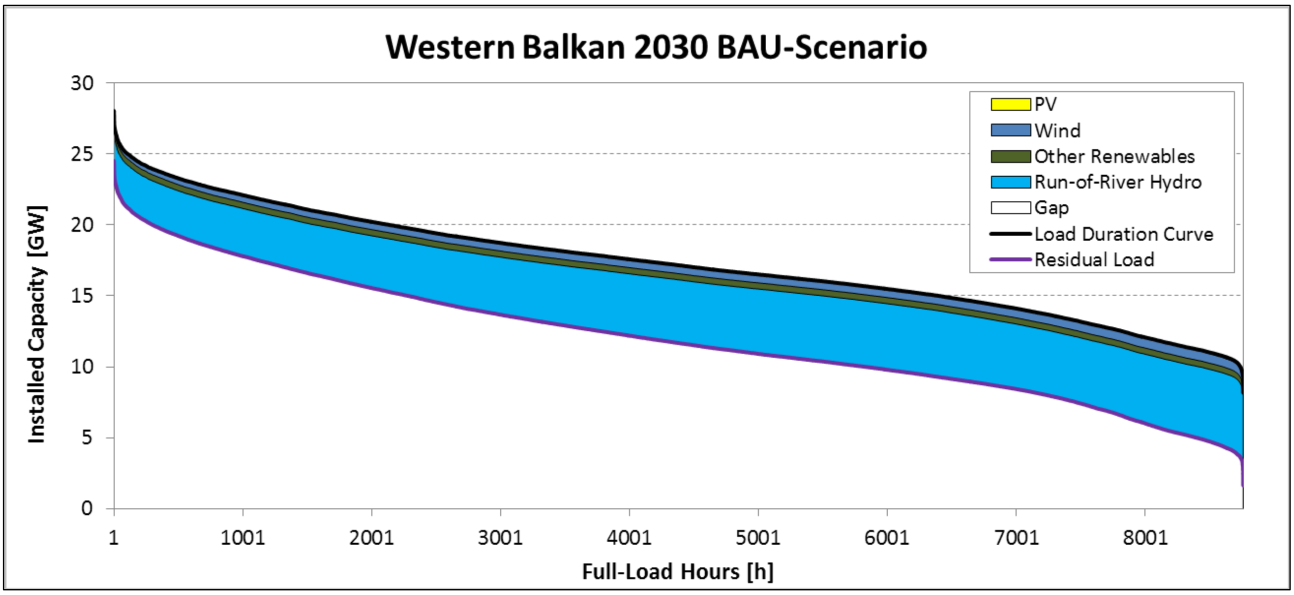


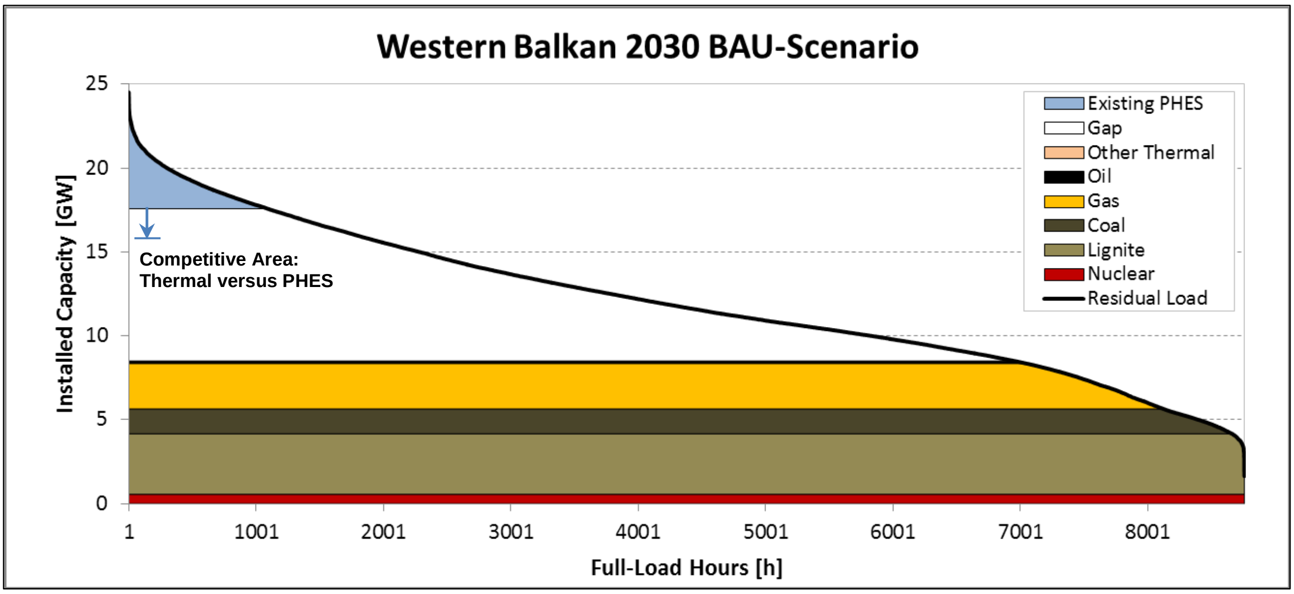


Supported by INTELLIGENT ENERGY EUROPE

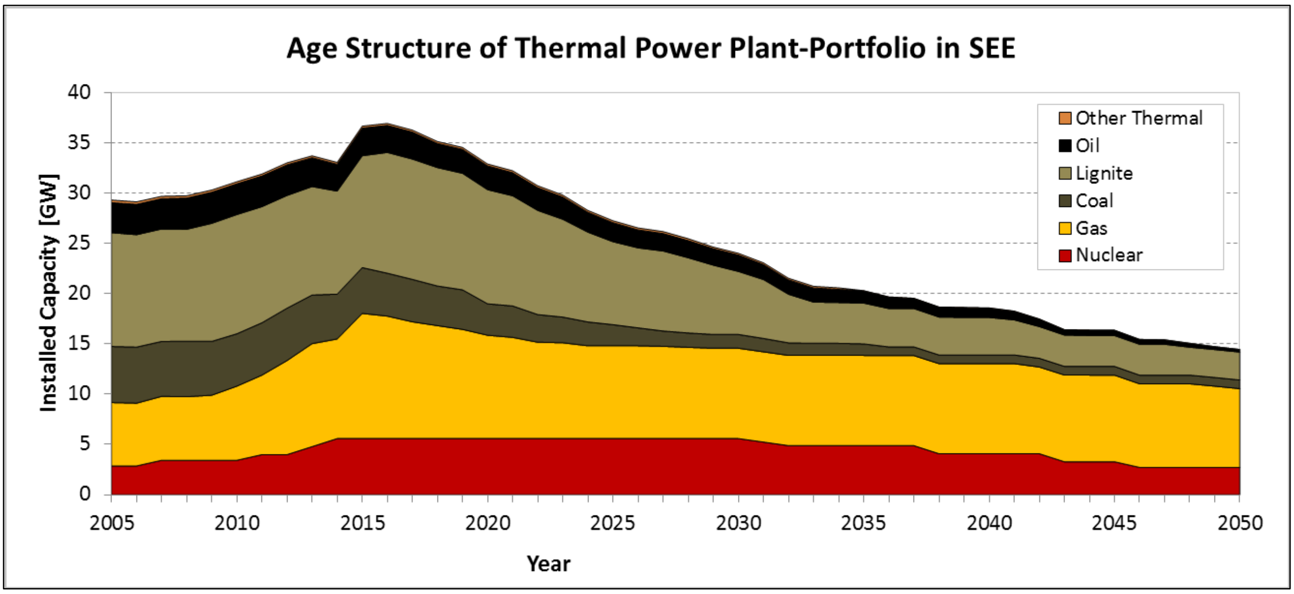
A4.2.2 Western Balkan (BAU scenario 2030)

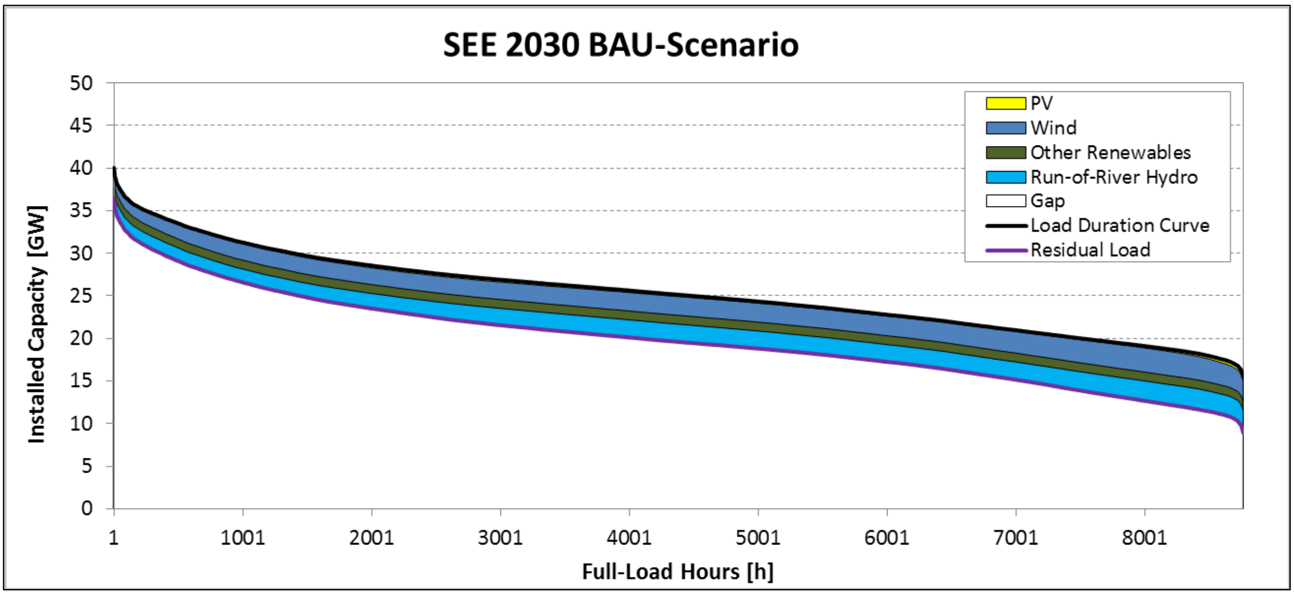


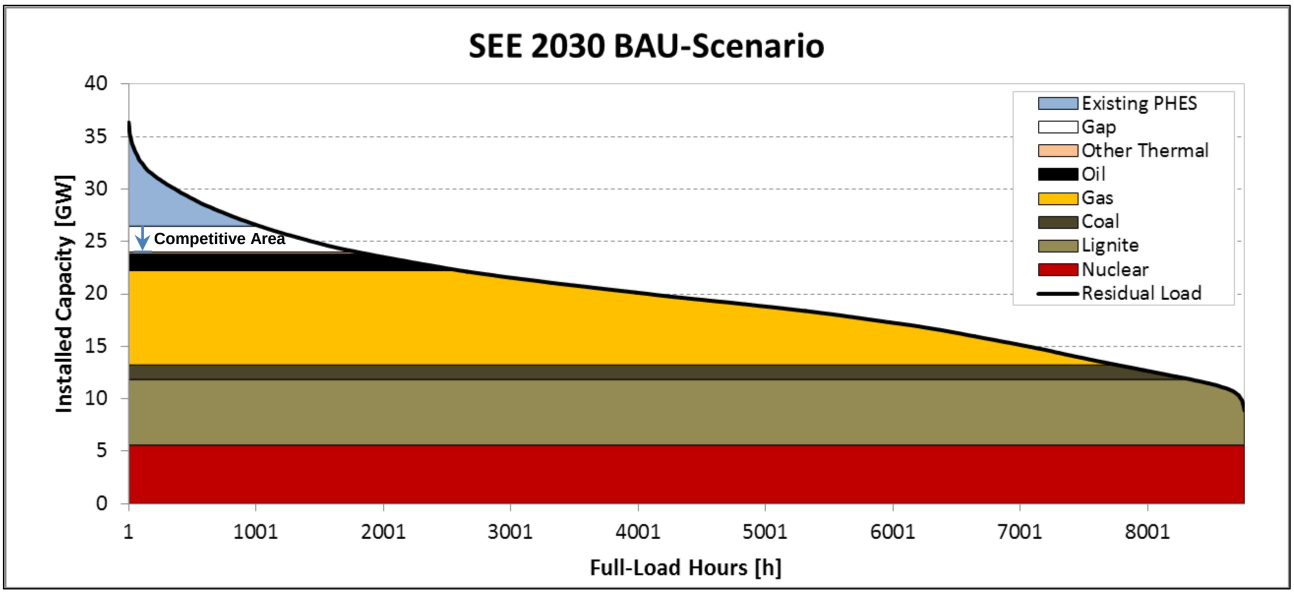




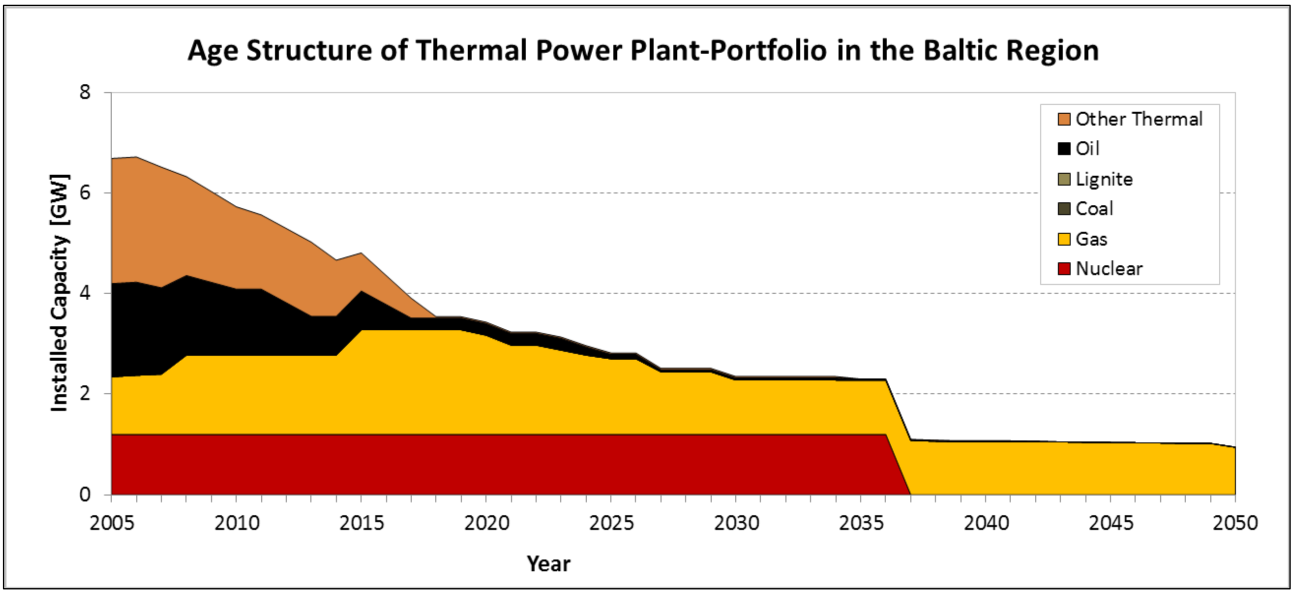
A4.2.3 South-Eastern Europe (BAU scenario 2030)

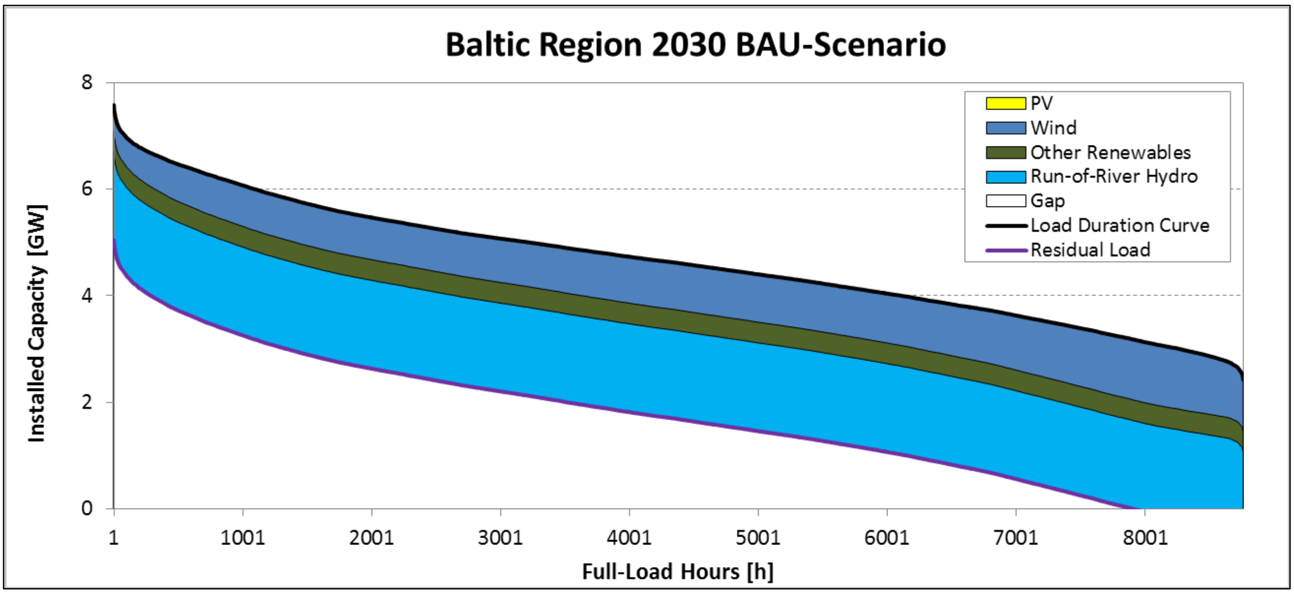


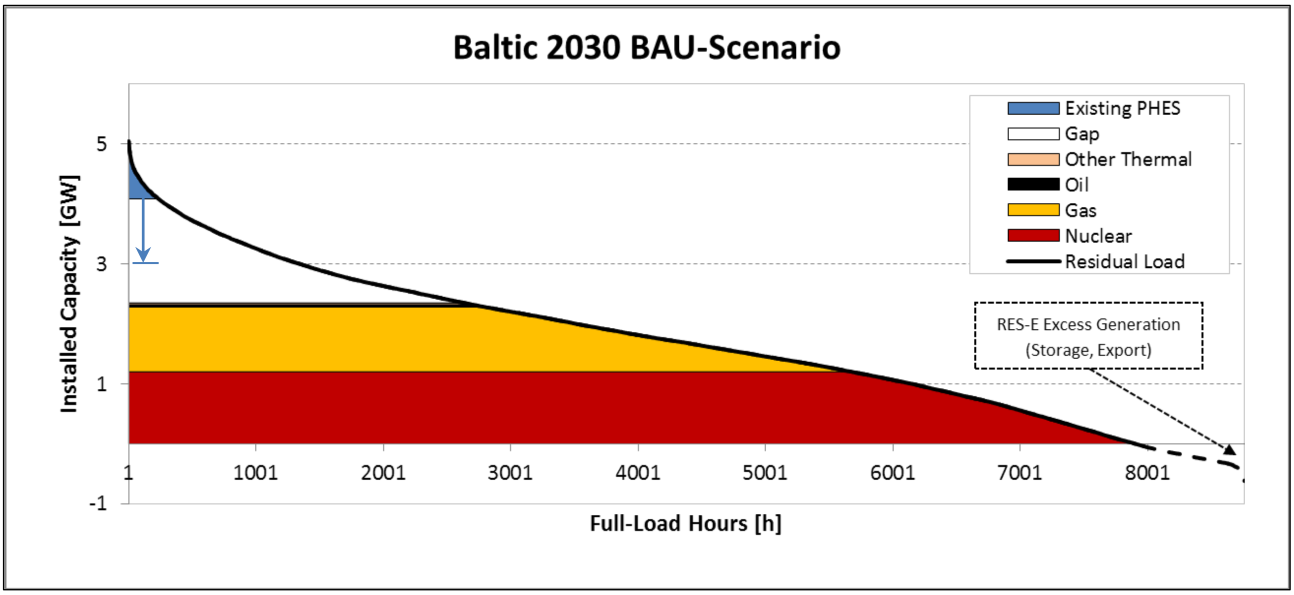




A4.2.4 Baltic Region (BAU scenario 2030)

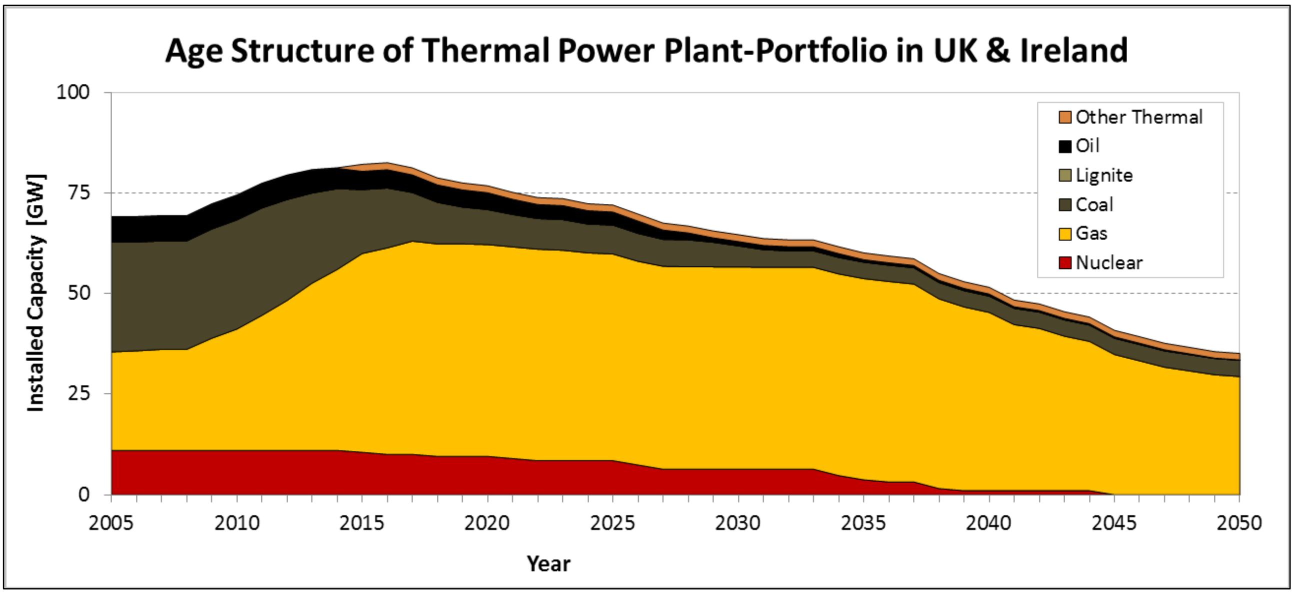


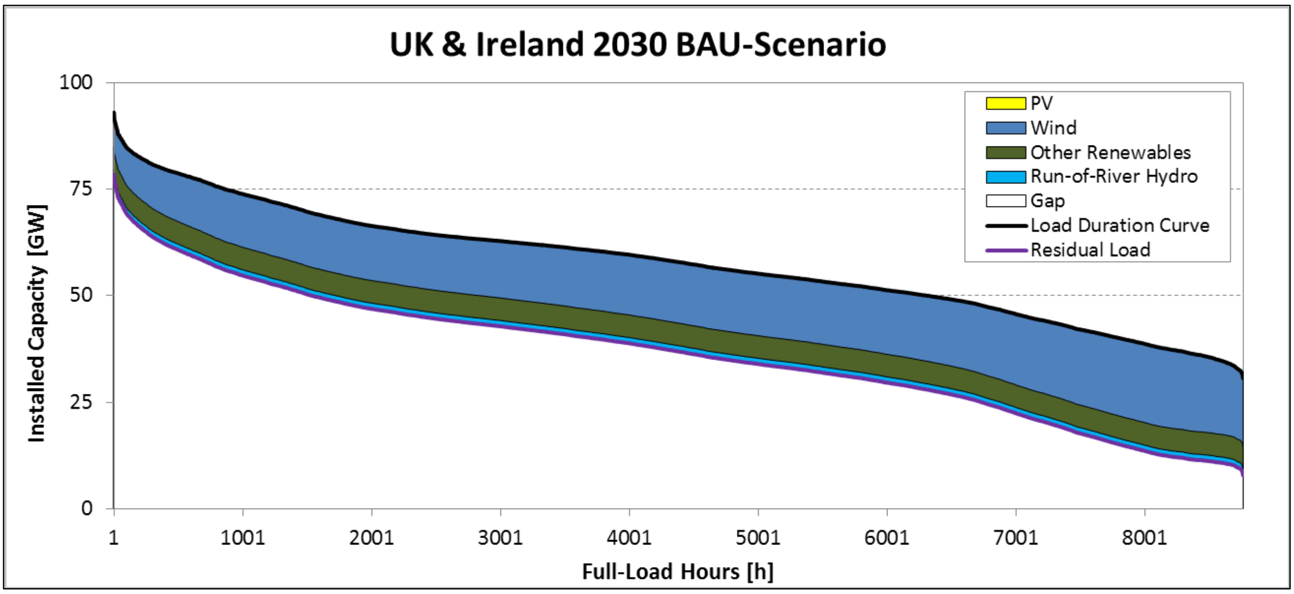


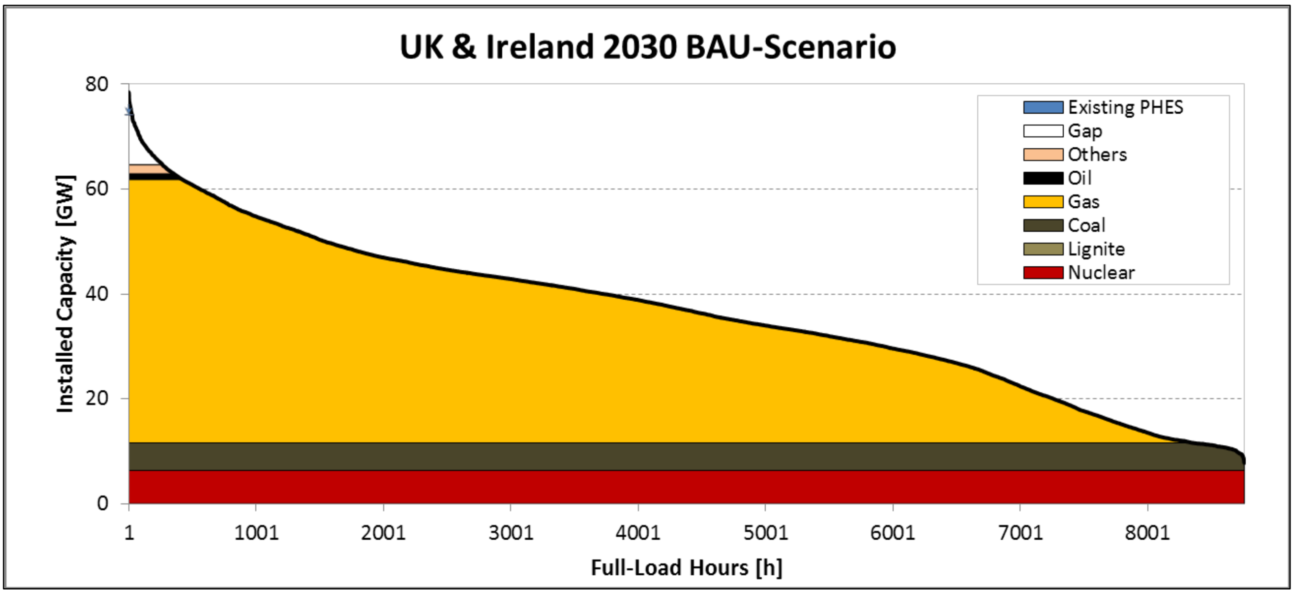


Supported by INTELLIGENT ENERGY EUROPE

A4.2.5 UK and Ireland (BAU scenario 2030)





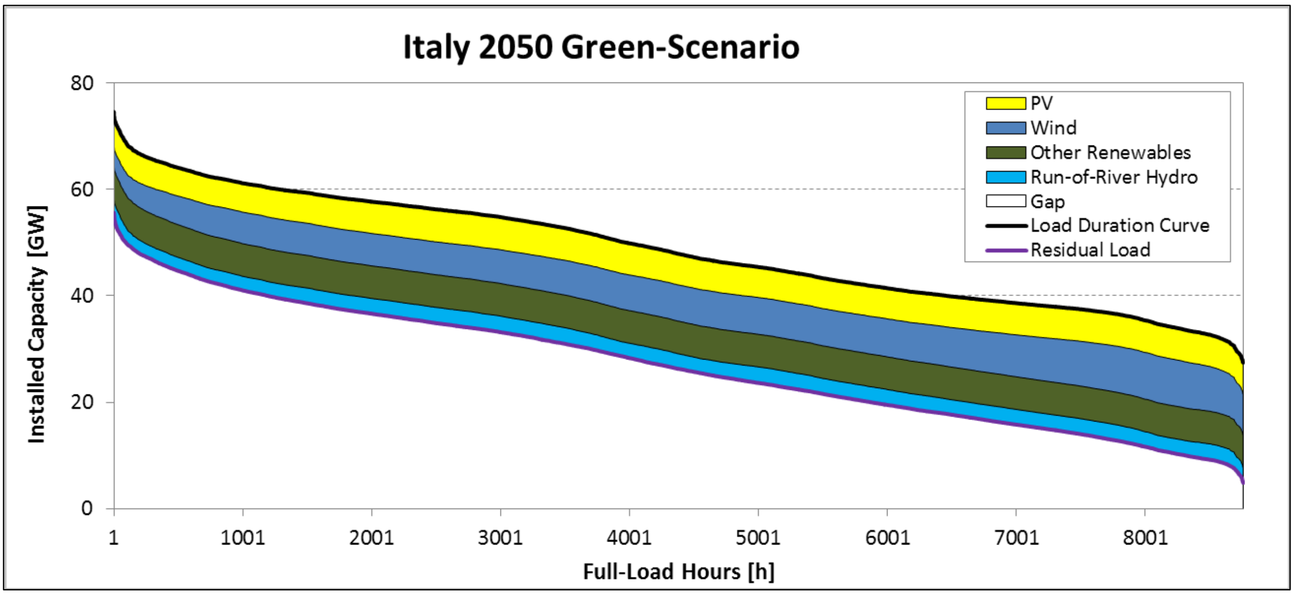


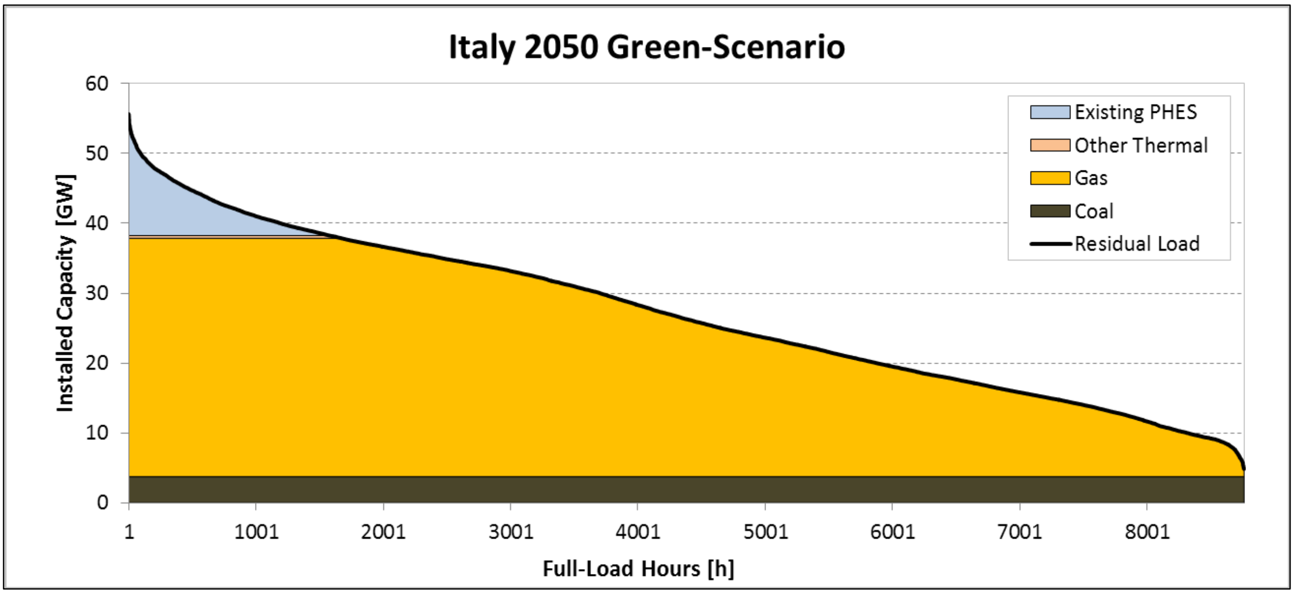
Supported by INTELLIGENT ENERGY EUROPE

A4.3 Further Results of the GREEN Scenario in the Year 2050

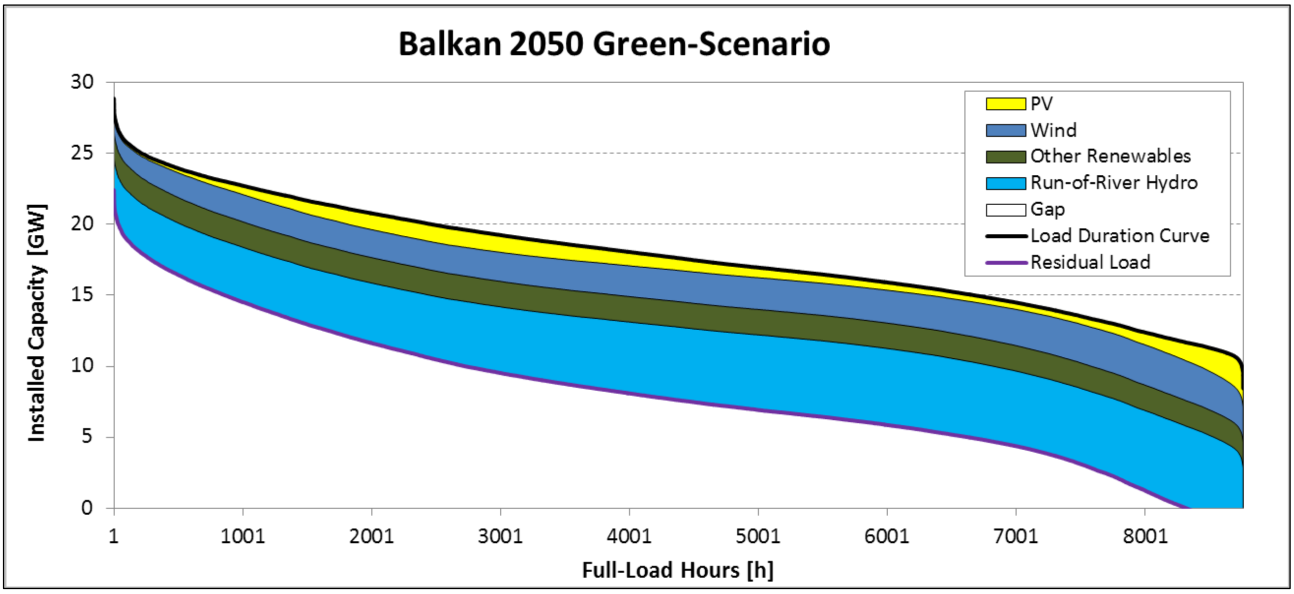
In the following sections selected results for the European electricity regions of Italy, Western Balkan, SEE, Baltic region and UK & Ireland are presented for the GREEN scenario in the year 2050. For each region the load duration & residual load curve and the coverage of the residual load curve with existing thermal power plants and PHES are given (two figures per regions in total).

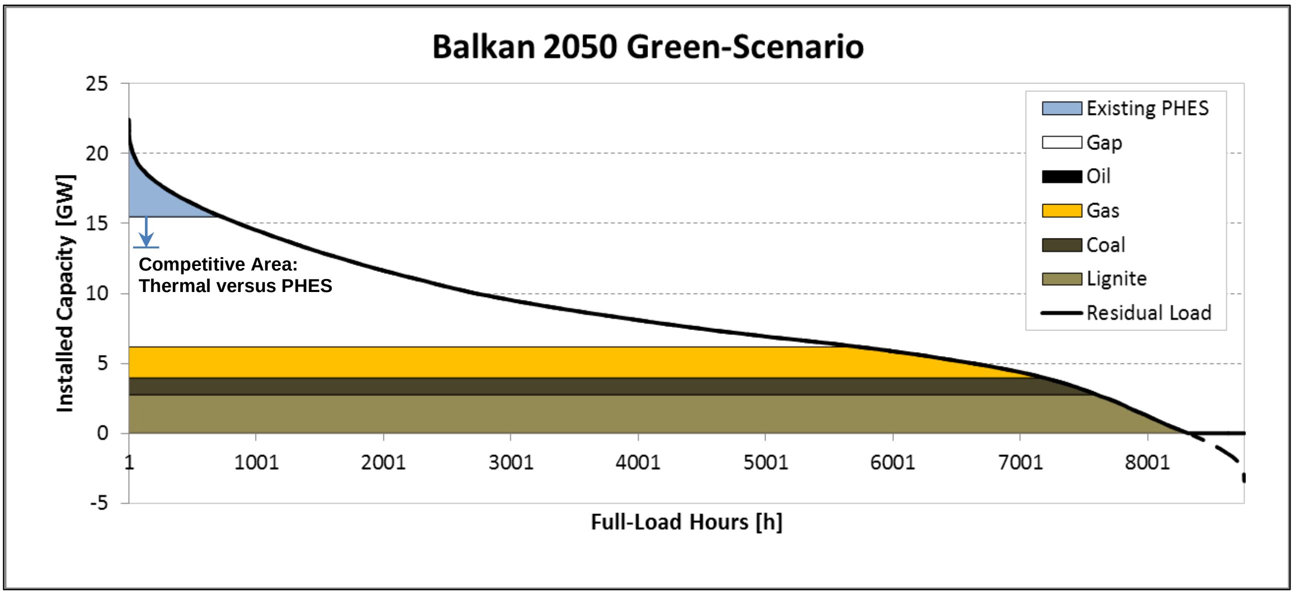
A4.3.1 Italy (GREEN scenario 2050)





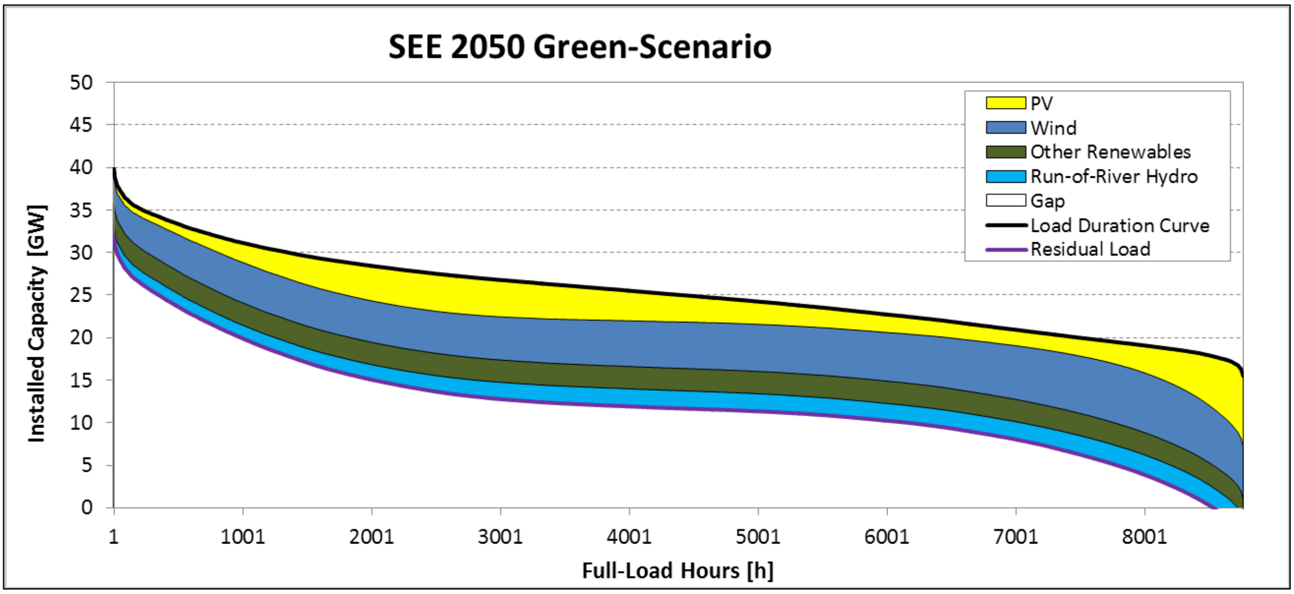
A4.3.2 Western Balkan (GREEN scenario 2050)

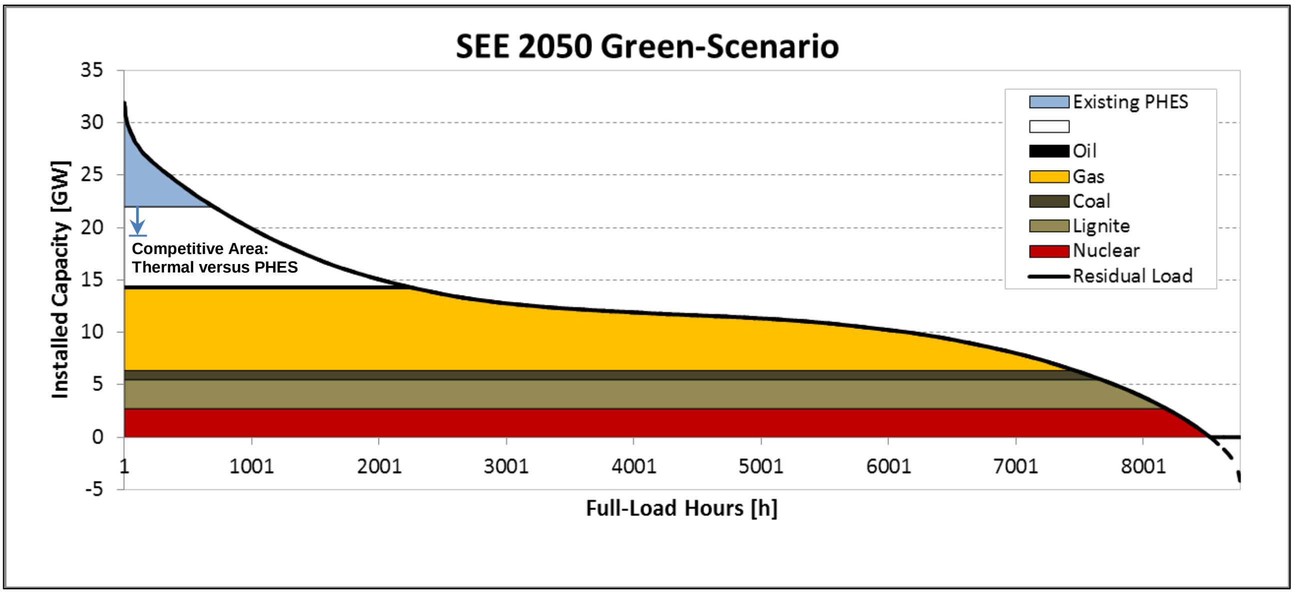




Supported by INTELLIGENT ENERGY EUROPE

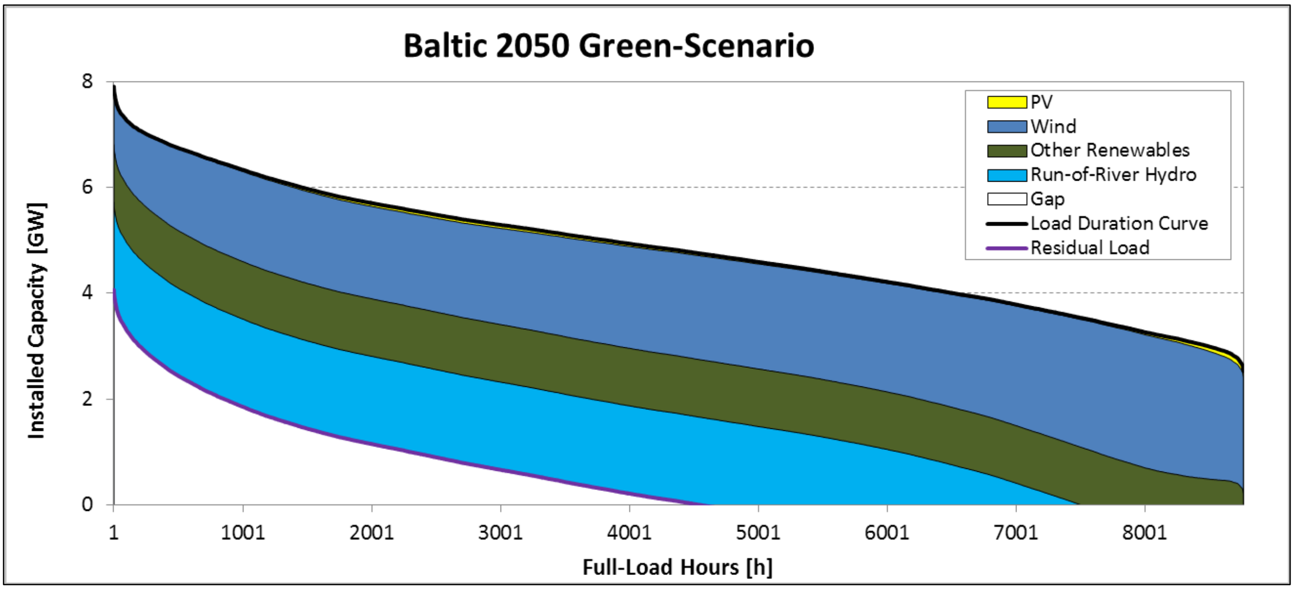
A4.3.3 South-Eastern Europe (GREEN scenario 2050)

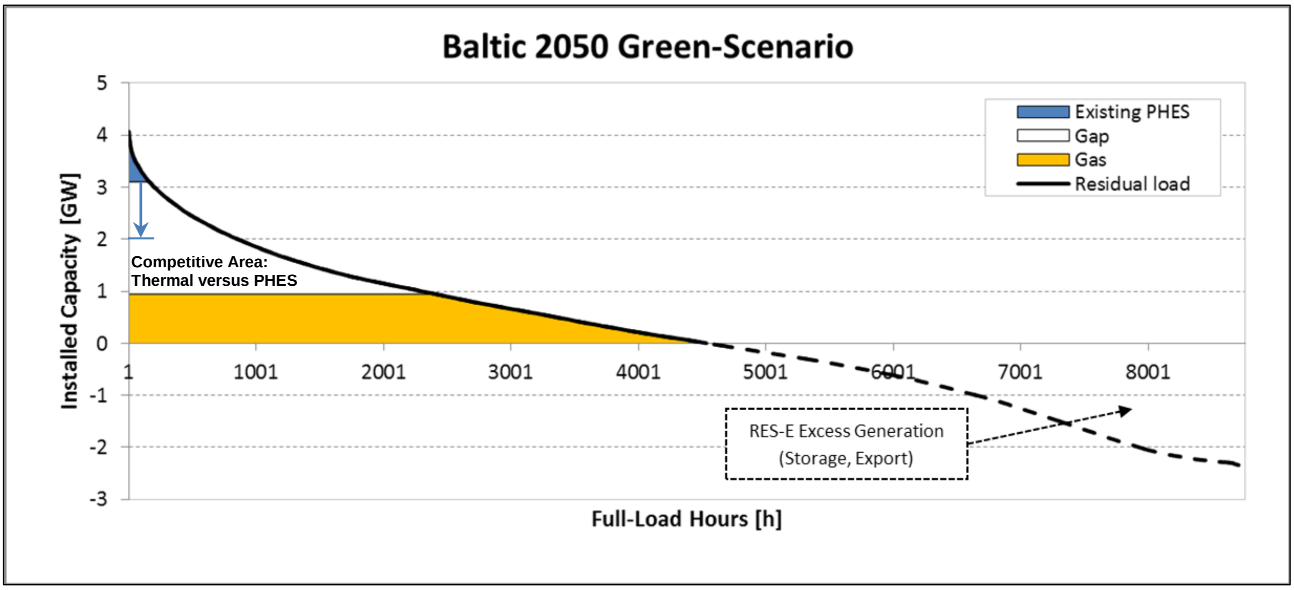




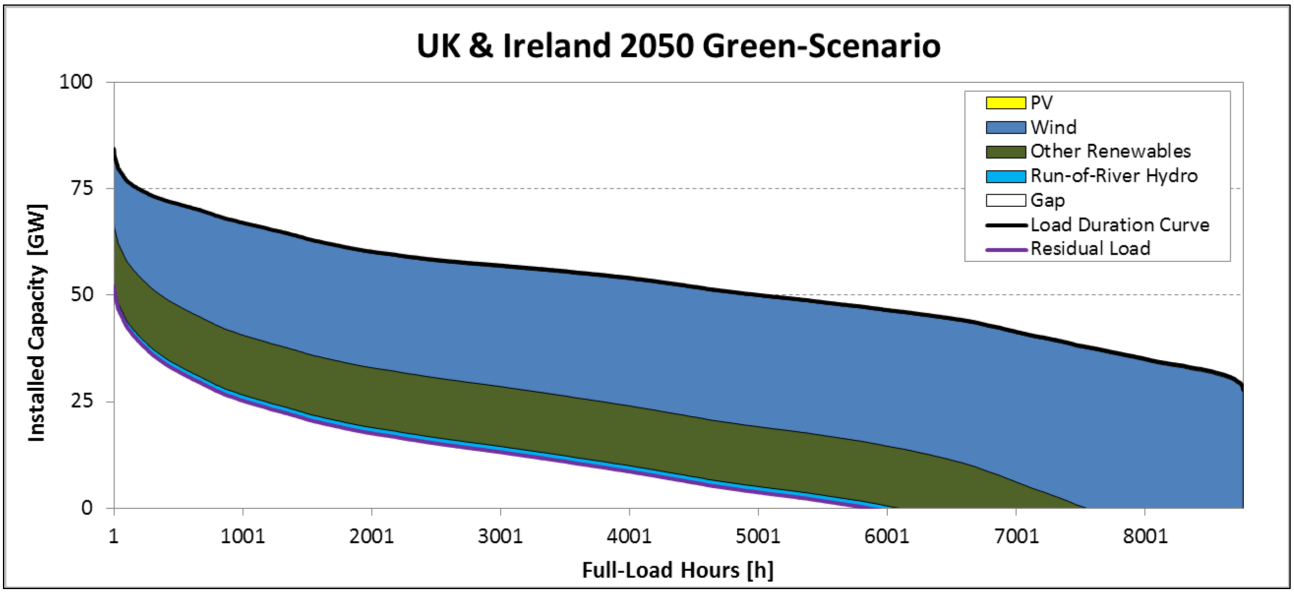
Supported by INTELLIGENT ENERGY EUROPE

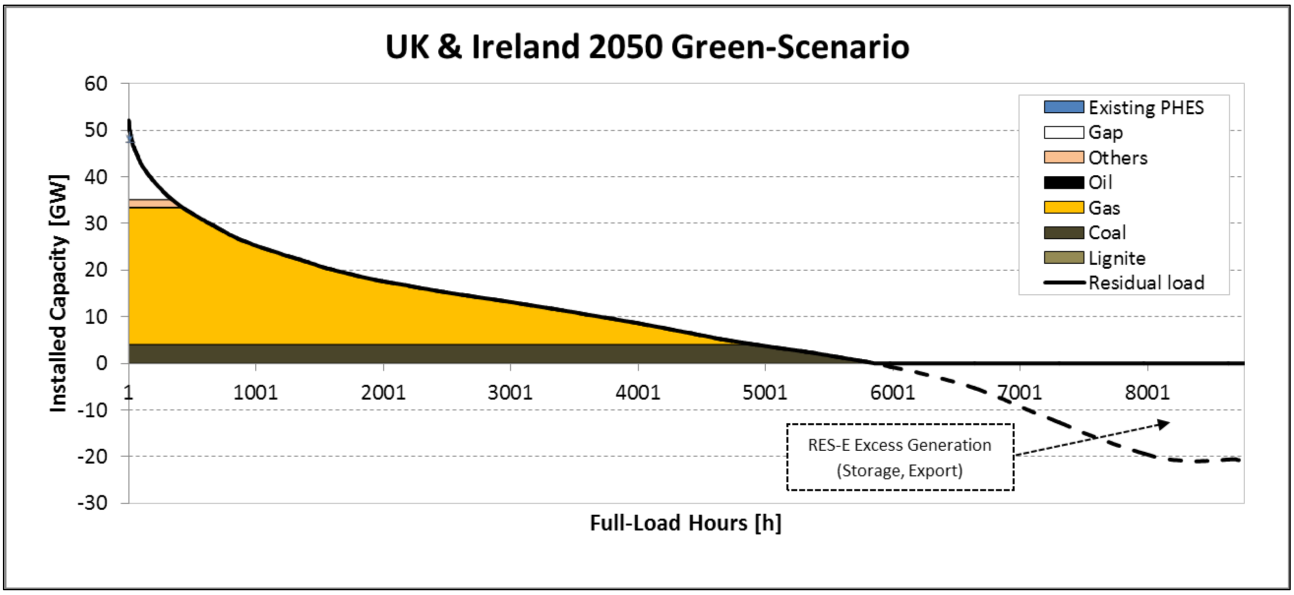
A4.3.4 Baltic Region (GREEN scenario 2050)





A4.3.5 UK and Ireland (GREEN scenario 2050)





Supported by INTELLIGENT ENERGY EUROPE

A4.4 Further Result Tables

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

Contribution of Transmission Expansion for Mitigation of Wind within the Regions and Management of Extreme Weather Events

	Within the Region		**Contributions from Outside ("Imports")**		**Contributions to other Regions ("Exports")**	
SEE	*Contribution in **SEE***		*Transmission Expansion to **CEE***		*Transmission Expansion to **CEE***	
	PHES	**Thermal**	**Moderate**	**Significant**	**Moderate**	**Significant**
	High (Existing)	High (Existing)	Limited	Limited (Anticorrelation Wind)	Limited	High (Anticorrelation Wind, PHES)
	High (New)	High (New)		Limited (Correlation Wind)		Limited (Correlation Wind)
			*Transmission Expansion to the **Western Balkan***		*Transmission Expansion to the **Western Balkan***	
			Moderate	**Significant**	**Moderate**	**Significant**
			Limited	Limited (Anticorrelation Wind)	Limited	High (Anticorrelation Wind, PHES)
				Limited (Correlation Wind)		Limited (Correlation Wind)
Baltic Region	**Within the Region**		**Contributions from Outside ("Imports")**		**Contributions to other Regions ("Exports")**	
	*Contribution in the **Baltic Region***		*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)	Limited	Limited (Anticorrelation Wind)
	High (New)	High (New)		Limited (Correlation Wind)		Limited (Correlation Wind)
			*Transmission Expansion to **CEE***		*Transmission Expansion to **CEE***	
			Moderate	**Significant**	**Moderate**	**Significant**
			Limited	Limited (Anticorrelation Wind)	Limited	Limited (Anticorrelation Wind)
				Limited (Correlation Wind)		Limited (Correlation Wind)

Contribution of Transmission Expansion for Mitigation of Wind within the Regions and Management of Extreme Weather Events

	Within the Region		**Contributions from Outside ("Imports")**		**Contributions to other Regions ("Exports")**	
Western Balkan	*Contribution in **SEE***		*Transmission Expansion to **CWE***		*Transmission Expansion to **CWE***	
	PHES	**Thermal**	**Moderate**	**Significant**	**Moderate**	**Significant**
	High (Existing)	High (Existing)	Low	Low (Anticorrelation Wind)	Limited	Limited (Anticorrelation Wind)
	High (New)	High (New)		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 **Italy***		*Transmission Expansion to **Italy***	
			Moderate	**Significant**	**Moderate**	**Significant**
			Limited	High (Anticorrelation Wind, Thermal)	Low	Limited (Anticorrelation Wind)
				Limited (Correlation Wind)		Low (Correlation Wind)
			*Transmission Expansion to **SEE***		*Transmission Expansion to **SEE***	
			Moderate	**Significant**	**Moderate**	**Significant**
			Limited	High (Anticorrelation Wind, PHES)	Limited	Limited (Anticorrelation Wind)
				Limited (Correlation Wind)		Limited (Correlation Wind)