DISSERTATION

Grid Infrastructure Needs and Costs for Renewable Technology Market Integration

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Abstract

Up to now, the majority of all scenario studies in the energy sector have been conducted on the basis of country-specific annual balances of conventional and / or renewable energy supply and demand. The long-term scenario analyses of infrastructure integration of RES performed in this thesis additionally take into account the interdependencies between regional and trans-national energy systems and also the needs and costs for corresponding grid infrastructures (for electricity, gas and heat) to enable large-scale RES deployment.

The renewable grid integration scenario generation philosophy is based on a storyline approach: two main driving forces are identified, public attitude and technological development, which open a 2-dimensional space with four quadrants. In each of the four quadrants several key, but uncertain parameters influencing RES grid integration (like RES technology cost, electricity demand, fuel-, CO_2-prices, etc.) are described in a single storyline. Therefore, there are four different storylines in total: *Red*, *Yellow*, *Green* and *Blue*. A sequence of models is used to determine the deployment of RES-Electricity / RES-Heating generation technologies and its grid infrastructures needs and costs (based on least-cost principles) in the time period up to 2050. Additionally, a linear optimization algorithm is implemented to analyse interdependencies of neighbouring regions and the importance of bulk electricity storage technologies for integrating large amounts of variable RES-Electricity (incl. mitigation of their effects). Three European countries (regions) are analysed in detail: Austria (Central Western Europe), Serbia (Western Balkan) and Spain (Iberian Peninsula).

The analysis of the electricity sector is conducted in the *Blue* storyline. In Austria the RES-Electricity share increases to about 78% in 2050 due high additional wind, photovoltaic (PV) and hydro generation. With its flexible power plant mix (e.g. pumped-hydro), Austria can significantly contribute to mitigate the variability problem of wind and PV generation in the Central and Eastern European countries in case of transmission grid investments. The Serbian power system has passed a difficult period of underinvestment and also destruction – a lot of rehabilitation is needed in the Serbian grid infrastructure. In *Blue*, thermal power will remain the main source for electricity generation besides hydropower in Serbia / Western Balkan region until 2050. The main challenges in Spain / the Iberian Peninsula are high levels of RES-Electricity generation surpluses due to variable wind and solar generation already in 2030. Additional backup conventional generation (e.g. gas turbines), electricity storage options (e.g. pumped-hydro, etc.), additional interconnection capacity (e.g. to France) and / or other flexible resources are strongly needed to balance the electricity system.

The analysis of the heating / gas sector is conducted in the *Yellow* storyline. The results show that – regardless which kind of heat grid infrastructure (or stand-alone technology / technology combination) currently exists in a region – a crucial long-term aspect in the further development of the entire portfolio of heating technologies and corresponding grid infrastructures is the future ambition of the implementation of end-use energy efficiency technologies on the demand side. Moreover, end-use energy efficiency implementation on the demand side finally also reacts upon the economics of the different energy carriers in the local / regional heat market and the corresponding network infrastructures.

Overall, the analyses in this thesis improve the understanding of grid infrastructure integration of RES technologies in different European regions under various constraints in the long-term.

Kurzfassung

Bisher wurde die Mehrheit aller Szenarien-Studien im Energiesektor auf der Basis von länderspezifischer jährlicher Balance von konventioneller und / oder erneuerbarer Energieversorgung und -verbrauch durchgeführt. Die langzeitige Szenario-Analyse zur Integration von erneuerbaren Energien (EE) in die Infrastruktur, die in dieser Arbeit durchgeführt wurde, berücksichtigt zusätzlich die Wechselbeziehung zwischen regionalen und transnationalen Energiesystemen und auch den Bedarf und die Kosten für die entsprechende Netz-Infrastruktur (für Strom, Wärme und Gas) um hohen EE-Ausbau zu ermöglichen.

Die Philosophie zur Erstellung von EE-Netzintegrationsszenarien basiert auf einem „*Storyline*“-Ansatz: zwei wesentliche Triebkräfte sind identifiziert, öffentliche Haltung und technologischer Fortschritt, die einen 2-dimensionalen Raum mit vier Quadranten aufspannen. In jedem der vier Quadranten werden wesentliche, jedoch unsichere Parameter in jeweils einer *Storyline* beschrieben, die die EE-Netzintegration beeinflussen (z.B. EE-Technologiekosten, Stromverbrauch, Treibstoff- und CO_2-Preise, etc.). Daher gibt es insgesamt vier verschiedene *Storylines*: *Red*, *Yellow*, *Green* und *Blue*. Eine Abfolge von Modellen wird verwendet um den Ausbau von EE-Strom / EE-Wärme Erzeugungstechnologien und deren Netzinfrastrukturbedarf und -kosten in der Zeitperiode bis 2050 zu bestimmen. Zusätzlich wird ein linearer Optimierungsalgorithmus erstellt, der die Wechselbeziehung von benachbarten Regionen und die Wichtigkeit von großtechnischen Stromspeichern zur Integration großer Mengen variabler EE-Stromerzeugung (inkl. Minderung ihrer Effekte) analysiert. Drei europäische Länder (Regionen) sind detailliert analysiert: Österreich (Zentral-West-Europa), Serbien (Westlicher Balkan) und Spanien (Iberische Halbinsel).

Die Analyse des Stromsektors ist in der *Blue Storyline* ausgeführt. In Österreich erhöht sich der Anteil von EE-Strom auf ca. 78% in 2050 durch zusätzliche Erzeugung von Wind, Photovoltaik (PV) und Wasserkraft. Bei Investition ins Übertragungsnetz kann Österreich mit seinem flexiblen Kraftwerkspark (Pumpspeicher) signifikant zur Minderung des Variabilitätsproblems von Wind- und PV-Erzeugung in Zentral- und Osteuropa beitragen. Das serbische Stromsystem hat eine schwierige Periode von Unterinvestition und auch Zerstörung hinter sich – viel Wiederaufbau und Erneuerung der Infrastruktur ist notwendig. In *Blue* bleibt auch weiterhin die thermische Stromerzeugung (neben der Wasserkraft) die wichtigste Energiequelle in Serbien / Westlicher Balkan bis 2050. Die wesentliche Herausforderung in Spanien / Iberische Halbinsel sind hohe Niveaus von EE-Stromüberschüssen durch variable Wind- und Solar-Erzeugung. Zusätzliche Reservekapazität konventioneller Stromerzeugungstechnologien (z.B. Gasturbinen), Stromspeicher, zusätzliche Übertragungsnetzkapazität und Leitungsanbindungen (z.B. nach Frankreich) und / oder andere Flexibilitätsquellen sind dringend notwendig um das spanische / iberische Stromsystem auszugleichen.

Die Analyse des Wärmesektors ist in der *Yellow Storyline* ausgeführt. Die Resultate zeigen, dass – unabhängig von der bestehenden Wärmenetzinfrastruktur (oder alleinstehender Technologie / Technologiekombinationen) – die Ambition in der Implementierung von Energieeffizienz beim Endverbraucher ein kritischer langzeitiger Aspekt in der weiteren Entwicklung des gesamten Portfolios von Wärmetechnologien ist.

Insgesamt haben die Analysen in dieser Arbeit das Verständnis von langfristiger EE-Netzintegration in verschiedenen europäischen Regionen unter diversen Bedingungen erhöht.

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Abbreviations

APG … Austrian Power Grid (TSO)
bbl … Barrel, 1 bbl ≡ 159 litres
CAES … Compressed Air Energy Storage
CCS … Carbon Capture and Storage
CEE … Central Eastern Europe, i.e. Czech Republic, Hungary, Poland and Slovakia
CHP … Combined Heat and Power
CO_2 … Carbon Dioxide
CSP … Concentrated Solar Power
CWE … Central Western Europe, i.e. Austria, Belgium, France, Germany, Luxembourg, the Netherlands, Switzerland and West Denmark
DC … Direct Current
DH … District Heating
EC … European Commission
EEMR … European Electricity Market Regions
EMS … Serbian Transmission System and Market Operator
ENTSO-E … European Network of Transmission System Operators for Electricity
EPS … Electric Power Industry of Serbia
EST … Electricity Storage Technologies
EU … European Union
GAMS … General Algebraic Modeling System
GJ … Gigajoule
GW … Gigawatt
HVAC … High Voltage Alternating Current
IEA … International Energy Agency
kW … Kilowatt
kWh … Kilowatt hour
LNG … Liquid Natural Gas
Mtoe … Mega tonne of oil equivalent, 1 Mtoe ≡ 11.63 TWh
MW … Megawatt
MWh … Megawatt hour
NIMBY … Not In My Backyard – is used to describe opposition by residents to a proposal for a new development (e.g. wind power plant) close to them
NREAP … National Renewable Energy Action Plan
OCGT … Open-Cycle Gas Turbine
OECD … Organisation for Economic Co-operation and Development

OHL	…	Overhead Line
PV	…	Photovoltaics
PJ	…	Petajoule
R&D	…	Research and Development
REE	…	Red Eléctrica de España (TSO)
RES	…	Renewable Energy Sources
RES-E	…	Renewable Energy Sources for Electricity generation
RES-H	…	Renewable Energy Sources for Heat generation
RoR	…	Run-of-River
SEE	…	South-Eastern Europe, i.e. Bulgaria, Greece and Romania
SS	…	Substation
t	…	Tonne, 1t ≡ 1,000 kg
TWh	…	Terawatt hour
TYNDP	…	Ten Year Network Development Plan (from ENTSO-E)
WEO	…	World Energy Outlook
yr	…	Year

1 Introduction

1.1 Motivation

Up to now, the majority of all scenario studies in the energy sector (e.g. PRIMES-model, World Energy Outlook, Green-X-model, etc.) have been conducted on the basis of country-specific annual balances of conventional and / or renewable energy supply and demand. Cross-country interdependences between neighbouring energy systems, on the one hand, and corresponding infrastructures needs (within a country as well as cross-border) for system integration especially of variable / intermittent renewable energy sources (e.g. wind, solar, etc.), on the other hand, are usually not taken into account.

The consideration of some of these lacking aspects mentioned above is one of the major innovations in the "*SUSPLAN*" project[1]. which takes into account the interdependencies between regional and trans-national energy systems in the regional scenario analyses of infrastructure integration of renewable energy sources (RES) and also the needs for corresponding grid infrastructures (for electricity, gas and heat) to enable large-scale RES deployment. The methodology developed within the "*SUSPLAN*" project forms the foundation for the additional analyses made in the course of this thesis.

Moreover, when looking into specific regions and countries the energy systems cannot be treated autonomously. In practise, they are influenced from outside the region / country and, therefore, the region has to be considered as a component within a trans-national energy infrastructure and vice versa:

- On the one hand, regional developments are significantly influenced by trans-national issues such as e.g. necessary extensions of electricity and gas transmission grids and also the expected high penetration of (variable) RES generation in some other neighbouring regions (like offshore wind).
- On the other hand, also opportunities and potentials for regions to react and contribute to the trans-national influences exist, e.g. (i) provision of system balancing services of flexible pumped hydro energy storage, (ii) decreasing energy imports from outside the region and, therefore, contributing to regional as well as trans-national security of supply.

When conducting the regional scenario analyses, it is expected that a variety of further interdependences between regional and trans-national levels "*appear*" and need an in depth consideration. Therefore, also the trans-national viewpoint needs to be emphasised in future scenario analyses taking into account the "*underlying*" regional scenario studies and their contributions (strengths as well as weaknesses) in a trans-national context.

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[1] Acronym for "PLANning for SUStainability", full project title is: "Development of regional and pan-European guidelines for more efficient integration of renewable energy into future infrastructure", www.susplan.eu.

1.2 Core Research Questions

This thesis analyses future renewable deployment scenarios (in terms of installed capacities and annual renewable electricity / heat generation) up to 2050 and also takes into account the corresponding infrastructure needs and costs both on regional as well as on trans-national level. In particular, the following research questions are addressed:

1. What RES-shares can be reached in different countries (namely Austria, Serbia and Spain) up to 2050 under different framework conditions?
2. What are the grid infrastructure needs and costs for RES-integration in completely different energy systems?
3. How does surplus electricity generation due to large-scale deployment of variable RES affect the future electricity system of European regions?
4. What is the role of bulk energy storage systems in facilitating RES-expansion in Europe?

1.3 Structure

The remaining content of this thesis is structured in the following chapters:

The next chapter, **Chapter 2**, focuses on the long-term scenario generation philosophy and the corresponding methodology. Due to the fact that the analyses cover a time horizon up to 2050 there exist a variety of regional and transnational uncertainties and options respectively – the establishment of a consistent set of empirical data is therefore crucial and also included in this chapter. Furthermore, also the selected European regions and countries for the analysis are introduced.

Chapter 3 provides a description of the methodology / modelling approach of the scenario analyses of the selected countries and regions. The main characteristics of the modelling tools used for the analyses of the electricity and heat sector are also briefly summarized. Moreover, also the link of the different models and the expected inputs and outputs for each step of the modelling activities are outlined.

In **Chapter 4** selected case study results (RES-deployment, infrastructure needs and costs) from the analysis of the electricity sector in the *Blue* storyline[2] are presented followed by the results from the analysis of the heat / gas sector in the *Yellow* storyline in **Chapter 5**. Both chapters are structured similarly, giving the results of Austria, Serbia and Spain sequentially. The results of the trans-national analysis of the European electricity market regions are also included in **Chapter 4**.

A synthesis of results from the electricity and heating / gas sector is given in **Chapter 6** and overall conclusions from the analyses are drawn in **Chapter 7**.

The **Appendix** provides additional input data and results and concludes this thesis.

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[2] Out of four different storylines one was taken for the analysis of the electricity sector and one for the heating / gas sector respectively – see section 2.1.2 for the description of the different storylines.

2 Renewable Grid Integration Scenario Generation based on the Storyline Approach

2.1 Storylines and Scenario Generation Methodology

Instead of applying a typical Business-As-Usual (BAU) scenario or alternative scenarios generated by variations of one or more parameters in relation to a BAU scenario in the analyses, the intention is to anticipate and describe fundamentally different possible future "*energy worlds*" enabling also "*structural breaks*" in long-term scenario generation (e.g. due to breakthroughs of new technologies, discontinuous changes of energy policies and / or public attitudes, etc.). Moreover, this approach is perfectly qualified to study much higher future RES penetration rates in Europe than written down in binding energy policy documents today. The results from the scenario generation analyses, therefore, rather describe what kind of RES generation and network infrastructures are needed to integrate RES generation; and even more important, what kind of policies, incentives, regulations, etc. do we need to get the most appropriate RES potentials utilized and grid infrastructures in place: where, when and based on which terms and conditions.

> The developed scenario generation philosophy verbally can be characterized as *"What if a certain development occurs?"* rather than *"What is the optimal (or most likely) development according to a given set of assumptions?"* Thus, a number of assumptions are made ex-ante to create a set of sufficiently different possible, but alternative future developments of energy systems both on regional and trans-national (global) level.

The set of different assumptions defining the different cornerstones of possible regional and transnational energy systems in the future is reconciled in so-called "*Storylines*". The description of these storylines (four in number) and also the quantitative results of corresponding analyses, however, cannot be interpreted as recommended *"optimal"* development of a future energy system. Instead, the scenario results must be regarded assumptions of a "*possible"* future development. Moreover, it is important to note that in the analyses none of the storylines is considered to happen more likely than another one!

2.1.1 Possible Future "Energy Worlds": Uncertainties and Options / Potentials

When further elaborating the different storylines, diverse categories of key "*influence parameters*" have to be structured in a way in order to describe the different possible, but alternative future developments of energy systems both on regional and trans-national (global) level. In detail, a distinction is made between the following different dimensions of parameters:

- *Region-independent* versus *region-dependent* developments;
- *Uncontrollable uncertainties* versus *controllable options / potentials;*

Selected examples of the most important candidates of parameters in each of the categories of "*influence parameters*" are listed below which determine the cornerstones of the scenario analyses (see also Figure 1):

- ***Region-independent, uncontrollable uncertainties:*** Fossil fuel prices of crude oil, natural gas or coal; wholesale price of CO_2; wholesale price of biomass[3]; investment costs of new and renewable technologies; capital costs (e.g. interest rates); other parameters determining international climate policies and / or international energy market developments.
- ***Region-dependent, uncontrollable uncertainties:*** Regional economic growth (regional gross domestic product); regional energy demand and load profile changes; regional energy policy focus (e.g. favouring and / or phasing out / in of single technologies like nuclear, Carbon Capture and Storage (CCS), etc.); subsidizing of single fuel types (e.g. lignite); regional energy policy goals (RES and energy efficiency) being more ambitious than international targets; venture capital access and availability; societal-economic aspects to increase public awareness and to favour public acceptance.
- ***Region-independent, controllable options:*** Availability and specification of several types of technologies for RES generation, end-use efficiency, network and network integration (incl. storage and load response).
- ***Region-dependent, controllable options:*** Share of regional potentials (RES generation, end-use efficiency, network routes, network integration technologies) realised and / or implemented; regional / municipal grid infrastructure planning policies (e.g. gas distribution grids versus district heating grids); regional financial support policies of new RES and end-use efficiency technologies; regional grid regulation and system balancing policies; regional Research and Development (R&D) budgets.

In Figure 1 the most important cornerstones of the scenario generation framework (following the nomenclature described above) are visualised:

- Each scenario on RES grid infrastructure integration consists of a possible, uncontrollable uncertain future development (described by storylines) and a combination of controllable parameters describing the settings of different options / potentials for how to act within an uncertain future (strategy / action plan).
- Each of the four different storylines consists of both region-independent (external) and region-dependent (internal) uncertain factors / development that cannot be directly controlled by the decision makers. On the contrary, each strategy / action plan contains a combination of technical, non-technical and other options which can be chosen, implemented and / or decided by decision makers.
- In general, this methodology enables a high number of scenarios (i.e. number of uncertain future developments multiplied by the number of strategies / action plans) to be generated in an analysed region. For practical reasons and focused interpretation of results, however, the number of both, storylines and strategies / action plans, has to be limited in the different regional scenario studies.

For scenario generation it is important to note that some settings of uncertainties and some options / potentials are common for all regions, while others are region specific. Thus, using this methodology in the scenario setup for the different regional RES grid infrastructure

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[3] Although biomass fuel costs at present have a regional component (and might also have to some extent in the future), an international biomass wholesale price most probably will be the reference price for biomass in the future.

integration studies will ensure a consistent and comparable starting point for the scenario analyses in several regions of particular interest.

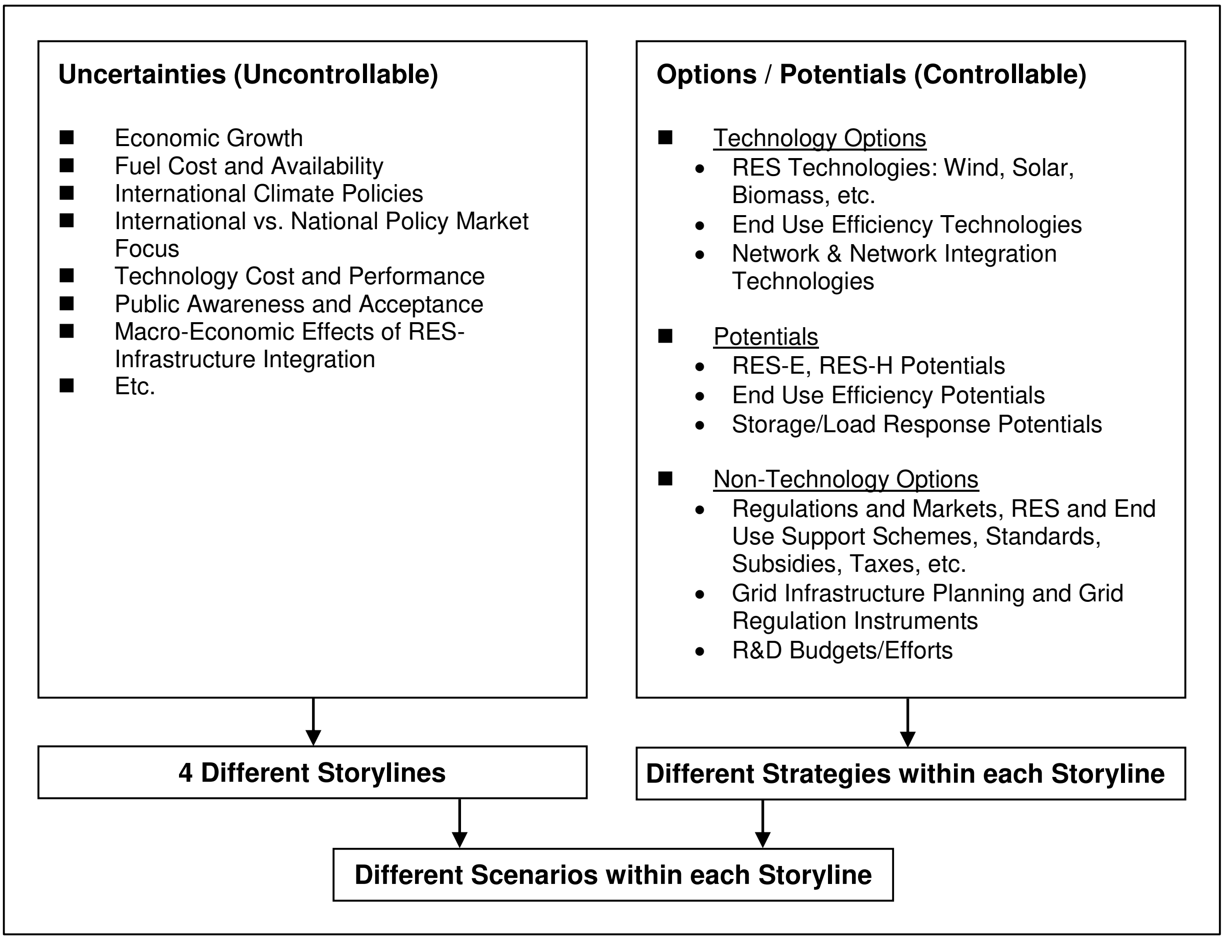

Figure 1: Scenario generation methodology

2.1.2 Description of the different Storylines

As already mentioned above, the combination of many uncontrollable, uncertain future developments (storylines) and settings of controllable parameters describing different strategies (action plans), finally, would lead to a multitudinous number of combinations (scenarios). Therefore, the amount of scenarios in the regional analyses has to be limited to be able to derive credible practical implementation plans for decision makers and stakeholders.

The most challenging task in this context is to limit the number of uncontrollable uncertain future developments. This is done by the identification of the primary driving forces according to the degree of uncertainty and relevance for the task (i.e. to analyse the more efficient integration of RES generation into future grid infrastructures).

Assuming two main driving forces (typically a "*hardware / technology*" and a "*soft*" driver) opens a two-dimensional space with four quadrants, see Figure 2. In each of the quadrants several uncertainties are described in a single storyline. Therefore, there are four storylines in total. Within a storyline different scenarios can be established and analysed by selecting the different strategies (action plans).

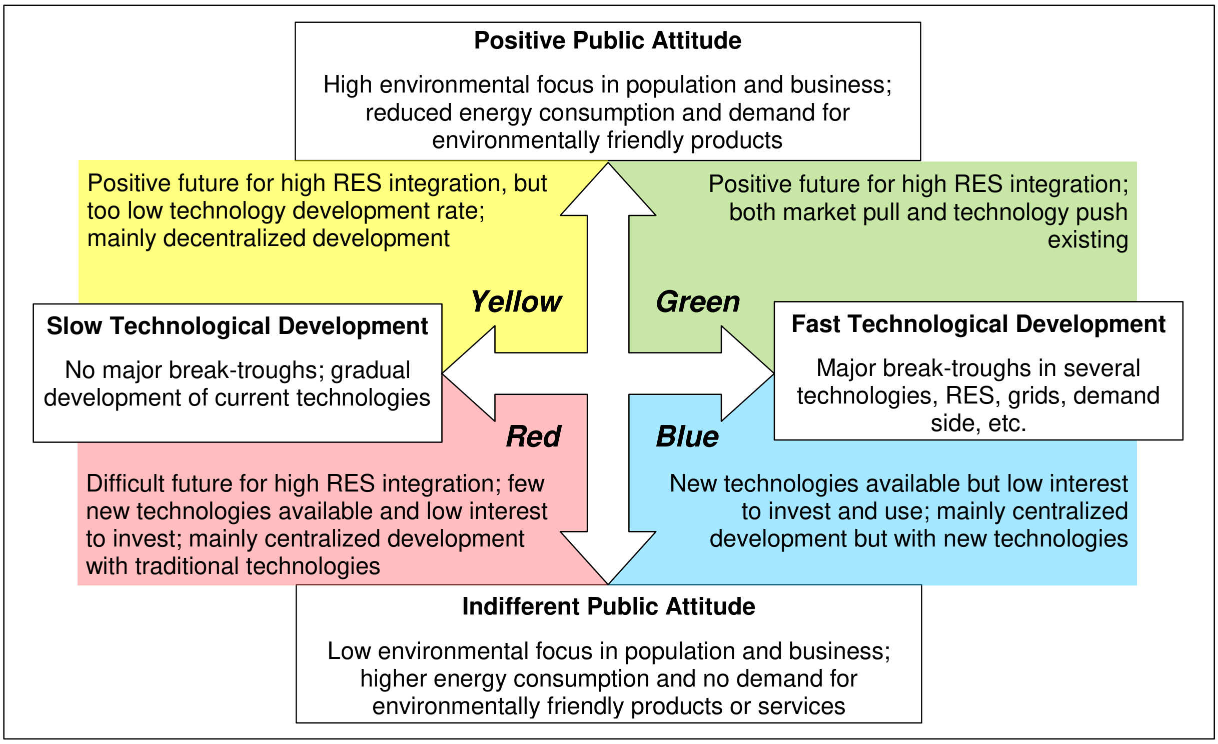

Figure 2: Overview of the four different storylines

In the following, the four different Storylines are named *"Green"*, *"Yellow"*, *"Red"* and *"Blue"* respectively.

> ***"Green" Storyline:*** *The green storyline describes the environmental friendly energy future. The energy system is developing in a direction which will prevent or at least limit climate changes. An alternative way of regarding the green storyline is by comparing with traffic lights. Green lights can be regarding as "continue in the same way". An even third interpretation is that biomass is utilised to a large extent in this storyline, and biomass is in most cases green.*
>
> ***"Yellow" Storyline:*** *Compared to traffic lights, yellow can be interpreted as "the time slot you have is limited". It is still possible to pass through or to change to a better direction towards sustainable energy systems. In addition, PV is specially mentioned as a significant part of the yellow storyline, and the sun is yellow.*
>
> ***"Red" Storyline:*** *Compared to traffic lights, the red storyline can be interpreted as "Stop! This is not a way to a sustainable future".*
>
> ***"Blue" Storyline:*** *Large-scale ocean energy and offshore-wind is an important part of this storyline, and the ocean is blue. In this storyline renewable energy is mainly produced centralized, far away from consumers' sites. This bears the problem that people do not get in touch with these sustainable technologies and also might not fully understand the need to behave environmental friendly. Thus, storyline "blue" is also indicating that people live their lives without much concern for the situation tomorrow.*

Before each of the four storylines is described more in detail, the basic assumptions and background information for the definition of the storylines are listed successively:

- There is a strong political will in Europe to promote sustainable development and security of supply in the energy sector. This strong political will results in significant use of necessary incentives and regulations for increased deployment of RES generation technologies.
- The share of RES in the future European energy system will be large. The use of conventional technologies like nuclear power plants and fossil fuel technologies (also with new CCS) will follow traditional infrastructure planning and operation strategies. Therefore, this already known aspect will not be explicitly analysed in detail. However, in the different storylines different penetration rates and emphasis of these technologies are assumed.
- Hydrogen will not be applied as energy carrier at distribution level in the given time perspective (up to 2050). If hydrogen is applied large-scale, it will be as bulk transport of energy or large-scale storage for the power sector. Electricity (e.g. electric vehicles) will turn out to be the most cost effective alternative to fossil fuels in the transport sector, but bio-fuels may in some storylines fill also a certain amount of the energy demand in the transport sector.
- The analysis focuses on stationary energy production and consumption, i.e. the transport sector itself is not explicitly analysed. However, electric vehicles and biofuels might influence the stationary energy balance (e.g. reduced bio-energy potentials for electricity and heat generation in case of biofuel use and applications in the transport sector).

The aspect of large-scale integration of different types of RES generation technologies is comprehensively addressed in the analysis. This creates different needs for infrastructures on different levels and dimensions:

- Transmission grid expansion needs both onshore and offshore to enable the utilization of the economies of scale of large-scale RES-Electricity generation of technologies like onshore and offshore wind, wave and tidal, Concentrated Solar Power (CSP), etc.;
- Distribution grid modernisation needs enabling the implementation of active grid elements and smart technologies interacting with several different kinds of grid users (smart grid concepts);
- Consideration of the interdependencies (and partly contrary objectives) between the needs of centralised top-down transmission grid infrastructure planning (favouring centralised RES-Electricity generation) and decentralised bottom-up smart grid concepts (favouring distributed RES-Electricity generation like PV, etc.);
- Consideration of the interdependencies between electricity, heat and gas grid infrastructures needs in case of combined-heat and power generation (e.g. biomass), on the one hand, and also switches of energy carriers “fuelling” particular energy services, on the other hand.
- Grid infrastructure needs to get spatial access to flexible electricity generation and storage technologies being qualified to contribute to the balancing of power systems with high shares of variable and intermittent RES-Electricity generation.

Besides others, the four storylines are constructed to cover all these kinds of aspects.

”Green” Storyline

There is a very high focus in Europe on environmental challenges and the need for reduction of CO_2 emissions. The awareness applies to the politicians and authorities at all levels, European as well as national and regional. Furthermore, it applies to the consumers, and since the consumers are mainly asking for commodities from companies which are acting in an environmental friendly way, also the industry has to reduce their emissions to a minimum. The *NIMBY*-factor[4] is hardly visible any more. Research and development of technologies relevant for reduction of CO_2 emissions have been given high priority for many years. The efforts have resulted in breakthroughs in many areas relevant for the energy sector.

In the *Green* storyline demand is low due to the consumers’ concern about acting in an environmental friendly way. Moreover, in *Green* all major technologies for RES generation are available at commercial level and large amounts of RES generation are possible at local, regional, national and trans-national level. The consumer has become a producer, and local production is very widespread.

In terms of grid infrastructures, in *Green* large-scale power grids are available to be implemented in an efficient way both onshore and offshore. On distribution level, smart grids are reality. Storage technologies for balancing variable and intermittency RES generation are available in terms of (pumped-) hydro power from the Alpine region as well as the Nordic countries. Also other new technologies are available and economically competitive for storage of energy both at local (end-user) as well as at aggregated level (e.g. different battery systems and also CAES[5]).

“Yellow” Storyline

There is a very high environmental concern among the consumers, which highly influences their demand for energy. This means that energy demand is low in the *Yellow* storyline. There have been limited breakthroughs in new technologies for RES generation as well as for transmission and distribution. However, due to the high environmental focus among people (“bottom-up” driver) there is a market pull for technologies for local production as well as for reduction of energy consumption.

However, since there are fewer penetrations of new and innovative technologies compared to the *Green* storyline, in *Yellow* more of energy demand reduction is caused by changes in behaviour and needs among consumers. In the transport sector there is also limited deployment of electric cars outside the main city centres, because there have hardly been any breakthroughs in battery storage technology.

In *Yellow*, new RES-Electricity generation is dominated by distributed solutions like PV. In general, RES production is mainly based on technologies that have been mature for many years. Finally, there have not been enough technological breakthroughs to make new large-scale energy efficient power grids commercially attractive in *Yellow*. However, there is some deployment of smart grid technologies due to the environmental focus among the consumers. Storage for balancing variable and intermittent RES generation is available in terms of (pumped-) hydro power from the Alpine region and to some degree from the Nordic countries. Also some decentralised solutions are available to contribute to balancing variable and intermittent RES production.

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[4] NIMBY: “Not In My Back-Yard”

[5] CAES: “Compressed Air Energy Storage”

"Red" Storyline

The *Red* storyline represents the most difficult future to achieve sustainable energy systems with high shares of RES. There have been limited breakthroughs in technology for RES production, transmission and distribution as well as for energy demand reduction.

In *Red*, energy demand is relatively high due to very low awareness among consumers. Some types of new technologies for demand reduction are available but the request for these technologies from consumers is very limited.

New RES generation is mainly established at municipal level. There is very limited interest for local (micro-) production. Furthermore, there have not been any necessary breakthroughs to establish significant new large-scale RES production on trans-national level. Therefore, in *Red* RES production is mainly assumed to be based on technologies that have been known for many years.

In terms of grid infrastructures, in *Red* large-scale offshore power grids are assumed to have no significant breakthroughs. Furthermore, smart grids are not worth to mention because the interest for local production and customer participation in the market is very limited. The vision from the first years of the 21st century about the consumer also becoming a producer has not become reality. Storage technologies for balancing variable and intermittent RES-Electricity generation are available in terms of (pumped-) hydro power from the Alpine region and to some degree from the Nordic countries. Eventually, at high enough electricity price levels the demand side may adjust their consumption to some extent in *Red* to contribute to balance intermittent RES generation.

"Blue" Storyline

In the *Blue* storyline, the development of the energy system in Europe is mainly driven by the politicians and authorities both European and national level. There has been a high focus on public R&D funding in the energy sector for many years. These efforts have finally resulted in *Blue* in the same level of breakthroughs in technology for RES production, transmission and distribution as in the *Green* storyline, but the investments have mainly been driven by authorities. Regarding technology for local production as well as energy reduction, the deployment is more limited due to low interest for the products. The *NIMBY* factor, furthermore, is a barrier for the establishment of both new RES production and new grid infrastructures.

In *Blue*, energy demand is high, since energy is still mainly a low-interest product among the European public. High energy demand is a result of both low interest in environmental questions and rather low energy prices.

In terms of RES-Electricity generation, in *Blue* large-scale and centralised solutions of RES-Electricity power plants are implemented (e.g. big offshore wind farms as well as CSP plants, etc.), supported by national and EU policy instruments.

Finally, in *Blue* large-scale power transmission grids are implemented and operated in an efficient manner both onshore as well as offshore. In contrast, smart grids have a very limited deployment. Storage technologies for balancing variable and intermittent RES-Electricity generation are available in terms of (pumped-) hydro power from Alpine countries as well as the Nordic countries. At high enough prices, the demand side reduces its consumption and flexible demand also contributes to balancing intermittency in RES production.

2.1.3 Time Horizon of the Analysis

As already mentioned in the introduction of this thesis, several long-term aspects of RES grid infrastructure integration in Europe both on regional and trans-national level are addressed in the analysis. More precisely, the time period 2030–2050 is of particular interest in the different in-depth scenario analyses on RES grid infrastructure integration.

However, this does not mean that RES deployment and the corresponding infrastructure needs in the time period from 2010–2030 are neglected. The time period 2010–2030 (and the already binding 20% targets on RES deployment and energy efficiency in the European Union in 2020) is treated as follows:

- Several existing studies analysing the European dimension of the future development of the energy systems and / or RES deployment and energy efficiency (mainly up to 2020; some of them up to 2030) have been analysed and incorporated in detail. Moreover, the most important studies (e.g. *'European Energy and Transport Outlook 2030'* (Capros, 2008) / *'Roadmap to 2050'* (EC, 2011) of the European Commission, *'World Energy Outlook'* of the International Energy Agency (IEA, 2011b), *Green-X*, others) also have been used as an input for the development of the four storylines, setting up the cornerstones of the different scenario analyses for the period 2030–2050.
- In the four different storylines it is assumed that the EU2020 targets are met at different points in time between 2020 and 2030. To be more precise, this means that for the analyses starting in 2030 it is not essential whether the EU2020 targets are perfectly met in practice in year 2020 or there are some delays. In order to take into account possible delays in practice, e.g. in the least ambitious *Red* storyline for the starting year 2030 those RES shares are assumed which should already have been implemented in year 2020 (assumption of a maximum 10 year's delay for the implementation of the EU2020 targets). On the contrary, in the *Green* storyline it is assumed that the EU2020 targets are perfectly met in practise in year 2020.
- In the starting year 2030 of the analyses in the four different storylines four different RES shares are assumed to be implemented. As already mentioned above, the least ambitious starting point is allocated to the most conservative storyline *(Red)* assuming the EU2020 targets to be implemented with a 10 years' delay in 2030. Several other scenarios in the remaining three storylines assume more ambitious (i.e. higher) RES penetration in 2030 as a starting point for the analyses.
- Finally it is important to note, that in each of the four different storylines different RES deployment scenarios are analysed (depending on the different strategy settings) for the time period 2030–2050. This means in particular, that within a storyline different scenario analyses on RES deployment and corresponding grid infrastructure needs are conducted. There is no inter-temporal "switch" between the different storylines in a single RES grid integration scenario analyses somewhere at a point in time in between 2030 and 2050.

2.2 Establishment of a Consistent Set of Empirical Data Describing Region-Independent Parameters

For the scenario analyses it is important to establish consistent empirical settings of the key region-independent parameters used. However, in this context it is not important to consider a high number of parameters describing the external-driven cornerstones of the energy systems in the different regions. In energy system modelling in general, the key parameters determining the cornerstones of energy supply and demand patterns (with or also without high shares of RES generation) can be limited to a few candidates. In the conducted analyses they comprise in particular:

- ***RES / RES-Electricity Deployment up to 2050:*** For each of the four different storylines four different empirical sets of future developments for both RES generation as a share of final total energy demand and RES-Electricity generation as a share of final total electricity demand are determined on aggregated European level up to 2050 (see Figure 3 and Figure 4 in detail).
- ***Final Energy / Electricity Demand up to 2050:*** Similar to future RES / RES-Electricity deployment the same sets have been established also for total final energy and total final electricity demand for each of the four storylines on aggregated European level up to 2050 (see Figure 5 in detail).
- ***RES / RES-Electricity Technology Cost up to 2050:*** Depending on global implementation rates of RES / RES-Electricity generation technologies also their specific technology investment cost decrease accordingly (mainly due to economies of scale in manufacturing). Therefore, different cost trajectories per RES / RES-Electricity technology and per storyline are considered in the analyses up to 2050 (see Figure 6 and Figure 7 in detail).
- ***Fossil Fuel-, CO_2- and Biomass Prices up to 2050:*** The necessity of consistent settings of future price scenarios for fossils, CO_2 and biomass is supposed to be straightforward in the scenario analyses. Again, in the different storylines different empirical settings of the future deployment of these key parameters are implemented. However, they are not set independently; they are rather explained and justified in comparison to other relevant studies and publications on international level (see Figure 8 in detail).
- ***Wholesale Electricity Prices up to 2050:*** Last but not least, the wholesale electricity market price level and its expected future development is the key benchmark determining the economics and phasing-in levels of RES-Electricity generation technologies. Economics in this context may also include some financial support instruments for new RES-Electricity generation technologies to compensate for the gap between the technology's higher electricity generation cost and the purely market-driven wholesale electricity price level. For the scenario analyses for each region a node is defined and scaled correspondingly in each of the four storylines up to 2050 based on a simplified European electricity market model (see also Appendix A.2 in detail).

In the following, the empirical settings of several of the key region-independent parameters described above – being of core relevance for the scenario analyses – are visualized and, furthermore, the most relevant references / sources and own assumptions are briefly explained.

2.2.1 RES / RES-Electricity Deployment up to 2050

Figure 3 and Figure 4 present RES and RES-Electricity deployment in the four different storylines on aggregated European level up to 2050 (Source: *Green-X*[6] modelling results up to 2030; own assumptions according to the long-term RES / RES-Electricity potentials and ambitions in energy efficiency implementation up to 2050 in the different European counties).

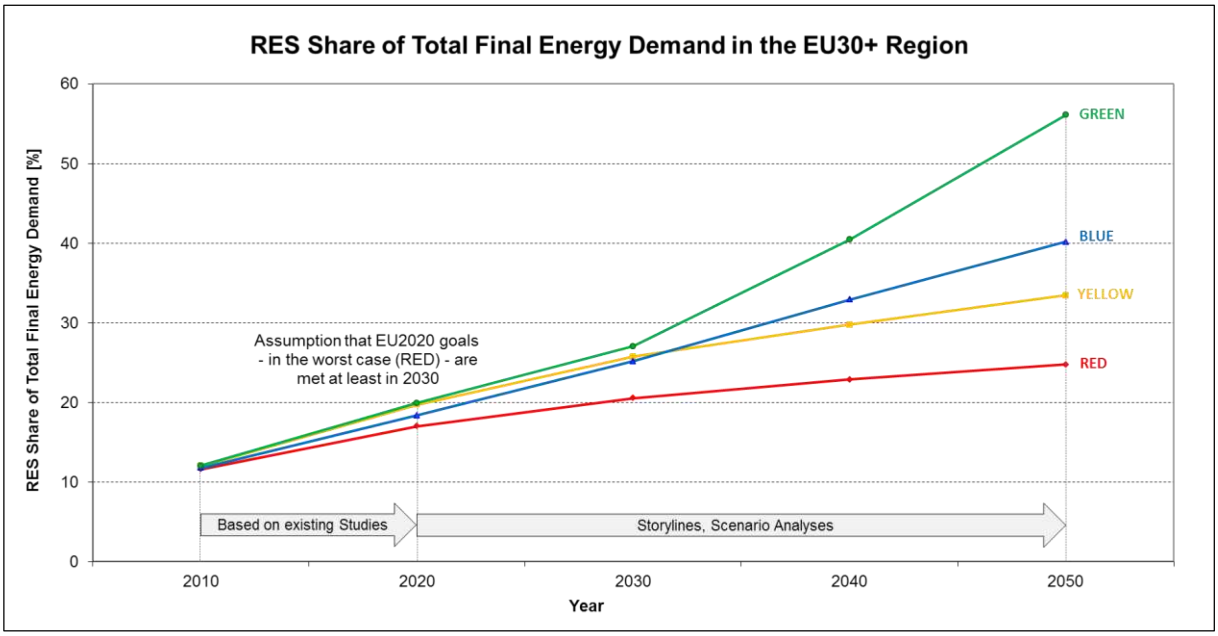

Figure 3: RES deployment as a share of total final energy demand on aggregated European level in the four different storylines until 2050 (Source: see text above)

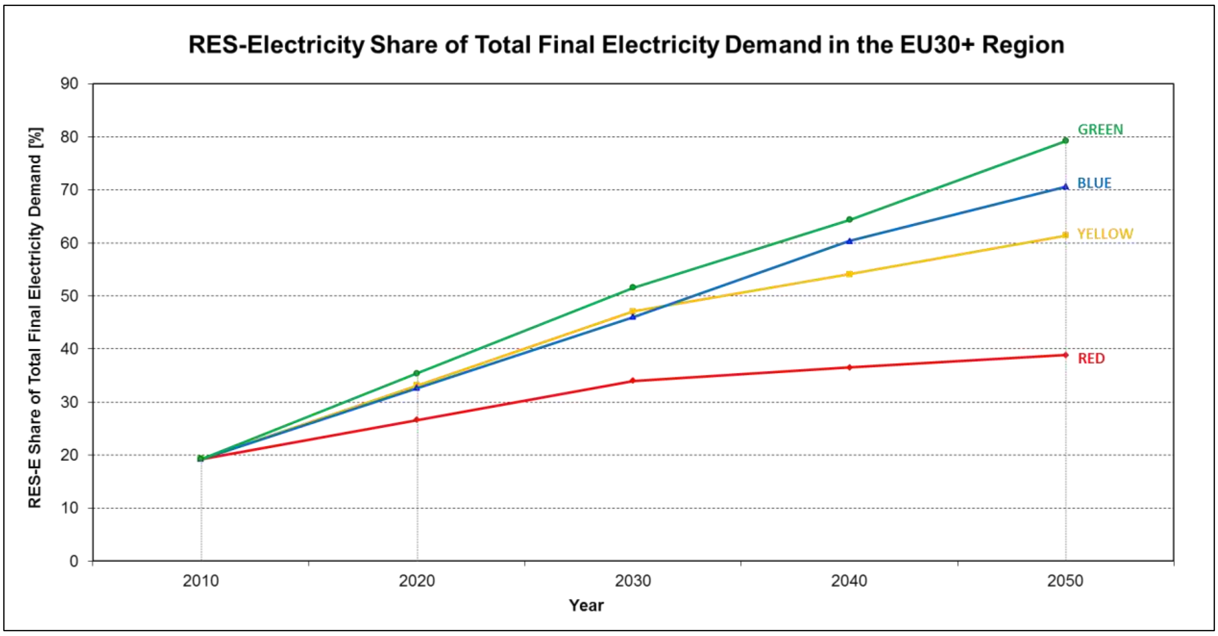

Figure 4: RES-Electricity deployment as a share of total final electricity demand on aggregated European level in the four different storylines until 2050 (Source: see text above)

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[6] See Huber et al., 2004a for more details.

2.2.2 Final Energy / Electricity Demand up to 2050

Figure 5 below presents final energy demand (electricity demand is not shown here; but the source is the same) in the four different storylines on aggregated European level up to the year 2050 (Source: data up to 2030 taken from *'European Energy and Transport Trends to 2030'* (Mantzos, 2006); own assumptions up to 2050).

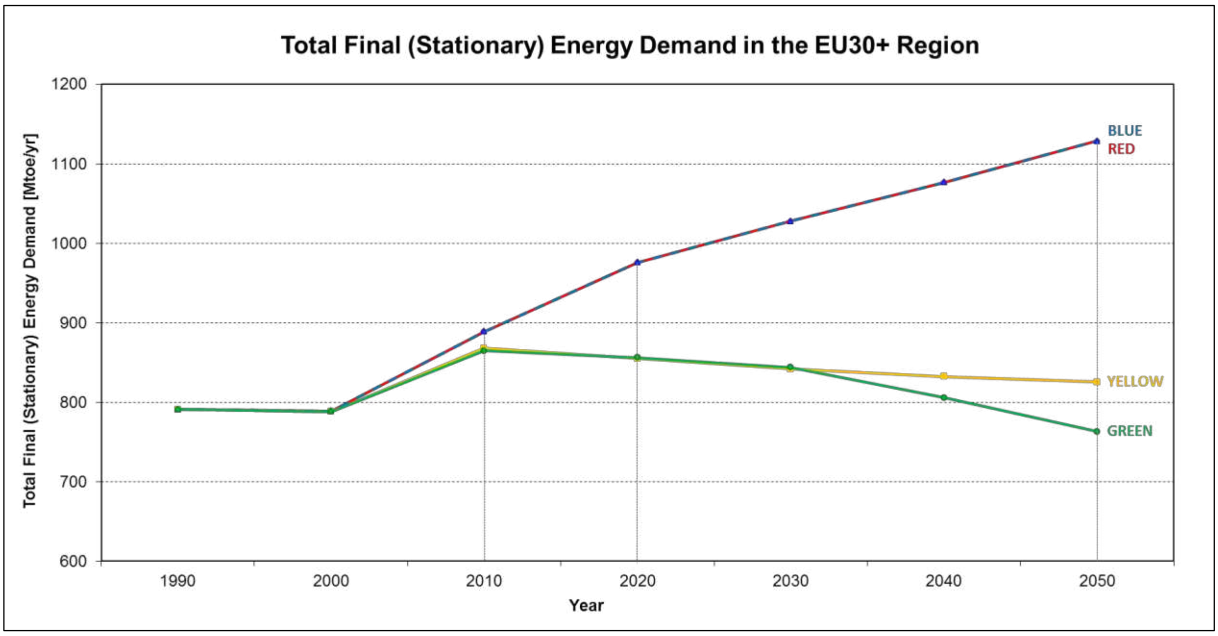


Figure 5: Total final stationary energy demand on aggregated European level in the four different storylines until 2050 (Source: see text above)

2.2.3 RES / RES-Electricity Technology Cost up to 2050

Figure 6 and Figure 7 present the future development of RES generation technologies' investment cost for the *Red* and *Green* storyline based on *Green-X* model (up to 2030) and extrapolation of gradients up to 2050. The reference year (100%) of technologies' investment cost is the year 2010.

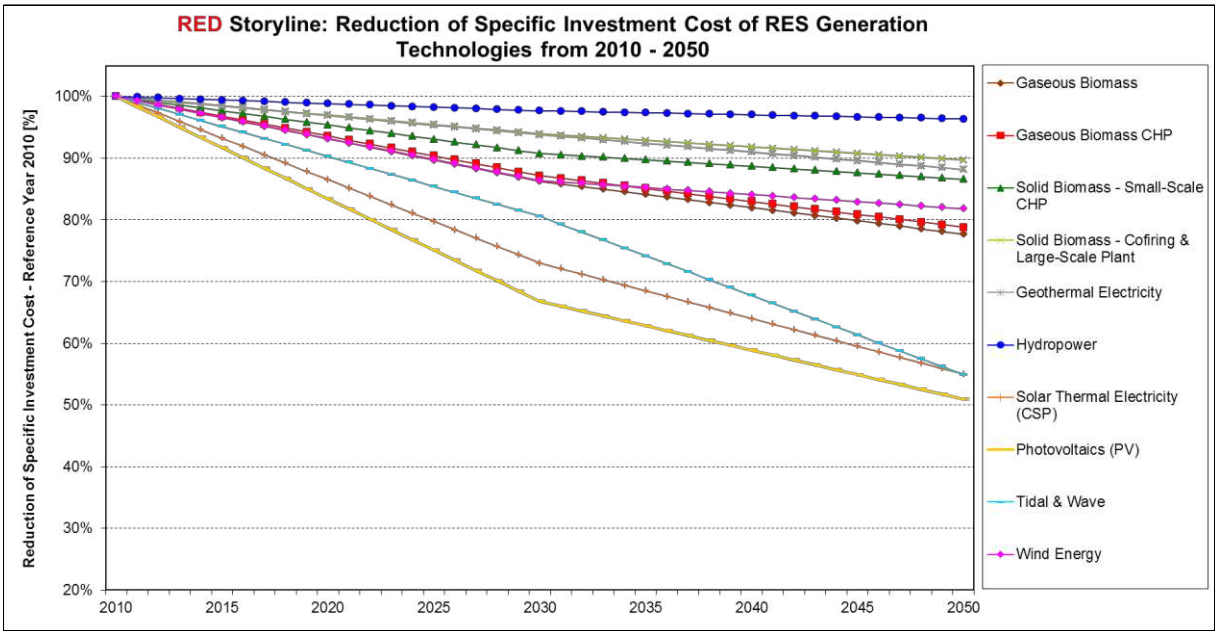


Figure 6: Development of the specific investment cost of different RES generation technologies in the *Red* storyline until 2050 (Source: see text above)

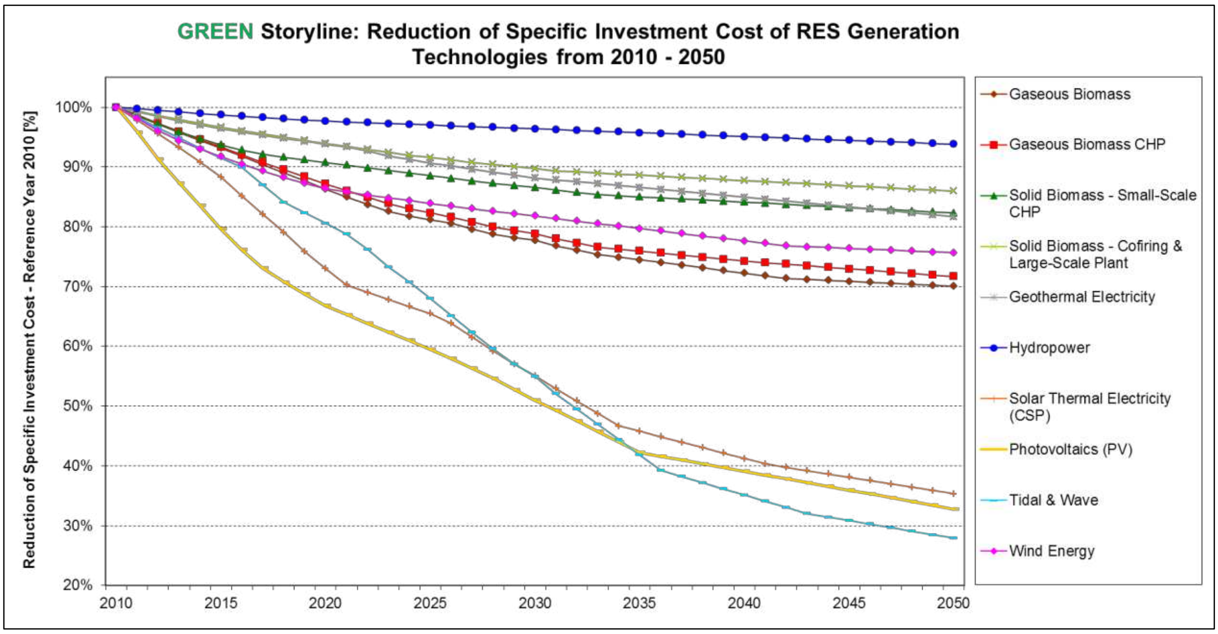


Figure 7: Development of the specific investment cost of different RES generation technologies in the *Green* storyline until 2050 (Source: see text above)

2.2.4 Fossil Fuel-, CO_2- and Biomass Prices up to 2050

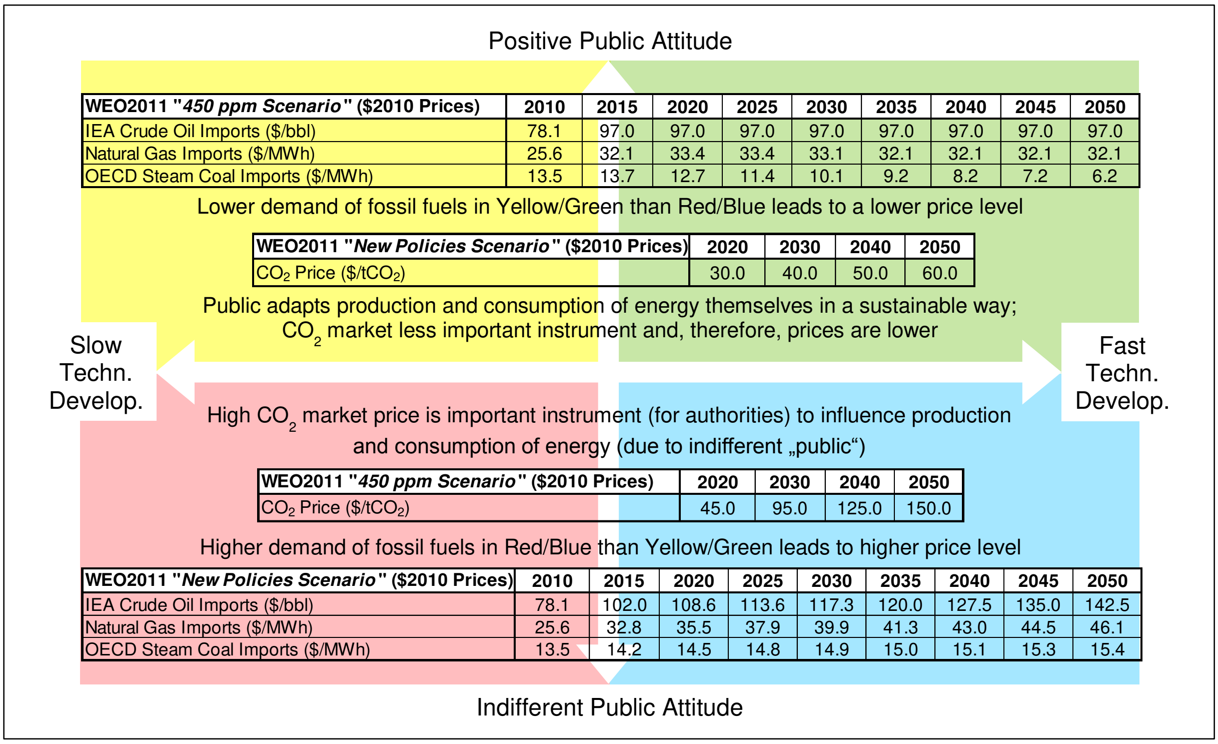
The following Figure 8 presents the expected future development of the fossil fuel and CO_2 prices in the four different storylines up to 2050.

Fossil Fuel and CO_2-Price Development up to 2050

In order to be able to set expected future price developments of fossil fuels and CO_2 in accordance with several important international studies (e.g. *'European Energy and Transport Trends to 2030'* (Capros, 2008) / *'Roadmap to 2050'* (EC, 2011) of the European

Commission, *'World Energy Outlook'* of the International Energy Agency (IEA, 2011b), *'Statistical Information'* of the U.S. Energy Information Administration of the Department of Energy (USEIA, 2012), Others), the major results on these price scenarios have been studied and compared. This comparison has led to the conclusion that the future price scenarios (i.e. *'Reference Scenario'* and *'450 ppm Scenario'*) of the 2011 publication of the World Energy Outlook (WEO2011)[7], in general, match with several other publications (small deviations can be explained by differences in assumptions in the different studies) and, therefore, are qualified to be used in the scenario analyses. Moreover, the empirical settings of the fossil fuel and CO_2 price scenarios of the WEO2011 are used in the storyline context as follows:

- The two different price scenarios of the WEO2011 are implemented in the modelling approach according to the expected demand and importance of fossil and CO_2 products in the different storylines. As the demand patterns of the two storyline couples *Red / Blue* and *Yellow / Green* are similar, the four different storylines are combined to two storyline-clusters.
- *Yellow / Green:* Due to lower demand of fossil fuels and decreasing importance of CO_2 instruments, the low price path of each of the two price scenarios of the WEO2011 is used.
- *Red / Blue:* Due to still high demand of fossil fuels and still high importance of CO_2 instruments, the high price path of each of the two price scenarios of the WEO2011 is used.



WEO2011 "*450 ppm Scenario*" ($2010 Prices)	2010	2015	2020	2025	2030	2035	2040	2045	2050
IEA Crude Oil Imports ($/bbl)	78.1	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0
Natural Gas Imports ($/MWh)	25.6	32.1	33.4	33.4	33.1	32.1	32.1	32.1	32.1
OECD Steam Coal Imports ($/MWh)	13.5	13.7	12.7	11.4	10.1	9.2	8.2	7.2	6.2

Lower demand of fossil fuels in Yellow/Green than Red/Blue leads to a lower price level

WEO2011 "*New Policies Scenario*" ($2010 Prices)	2020	2030	2040	2050
CO_2 Price ($/t$CO_2$)	30.0	40.0	50.0	60.0

Public adapts production and consumption of energy themselves in a sustainable way; CO_2 market less important instrument and, therefore, prices are lower

High CO_2 market price is important instrument (for authorities) to influence production and consumption of energy (due to indifferent „public")

WEO2011 "*450 ppm Scenario*" ($2010 Prices)	2020	2030	2040	2050
CO_2 Price ($/t$CO_2$)	45.0	95.0	125.0	150.0

Higher demand of fossil fuels in Red/Blue than Yellow/Green leads to higher price level

WEO2011 "*New Policies Scenario*" ($2010 Prices)	2010	2015	2020	2025	2030	2035	2040	2045	2050
IEA Crude Oil Imports ($/bbl)	78.1	102.0	108.6	113.6	117.3	120.0	127.5	135.0	142.5
Natural Gas Imports ($/MWh)	25.6	32.8	35.5	37.9	39.9	41.3	43.0	44.5	46.1
OECD Steam Coal Imports ($/MWh)	13.5	14.2	14.5	14.8	14.9	15.0	15.1	15.3	15.4

Figure 8: Expected development of the fossil fuel (crude oil, natural gas, coal) and CO_2 prices up to 2050 in the *Red / Blue* and *Yellow / Green* storylines (Source: see text above)

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[7] WEO2011 (IEA, 2011b) was the latest available version of the publication when the analyses were made.

Biomass Price Development up to 2050

In the scenario analyses it is assumed that there will be a common European market for biomass in the medium- to long-term, resulting in a converging international biomass wholesale price. Derived from the *'RES2020'* project[8], where several relevant country-specific biomass fraction and cost data are available for all EU27 Member States (incl. Norway), an average biomass price of 6 €/GJ is taken as starting point for 2010 for several of the four storylines. Moreover, roughly 80% of the biomass cost values in the different countries are within a range of 2 €/GJ to 9 €/GJ, with a decreasing trend for moderate biomass use towards the future.

In the storyline context the empirical settings of the biomass wholesale prices up to 2050 have been set as follows[9]:

- Due to the fact that in the *Red* storyline demand for biomass is assumed to be the lowest (compared to other storylines), a linear price decrease from 6 €/GJ in 2010 to 5 €/GJ until 2050 is foreseen. In the *Blue* storyline demand on biomass is slightly higher than in *Red* and, therefore, a constant biomass price of 6 €/GJ remains until 2050.
- In the two other storylines, *Green* and *Yellow*, demand on biomass is significantly higher and, therefore, increasing biomass wholesale prices are expected until 2050 reaching price levels of 8 €/GJ and 10 €/GJ for *Green* and *Yellow* respectively.

2.2.5 Wholesale Electricity Prices up to 2050

The wholesale electricity market price development in the four different storylines is not set exogenously; it is modelled endogenously with a European electricity market model where – among others – the empirical settings of parameters described above (like fossil fuel-, biomass- and CO_2 prices, RES-Electricity generation per technology, electricity demand on country-level, etc.) are used accordingly.

For modelling the European electricity market on an annual basis up to 2050, the model *'EMPS'* has been empirically scaled for each of the four storylines correspondingly for the scenario analyses (see section 3.1.1 for further details).

The *EMPS* model is a socio-economic electricity system model that can handle systems with large shares of conventional and variable electricity generation as well as long- and short-term storage options. Basically it is a stochastic optimization model which calculates a minimum cost strategy for the operation of an electricity system. Each European country is considered as a single node (characterized by an endogenously determined internal supply and demand balance – see also Appendix A.2) with distinct import and export transmission capacities to the neighbouring countries.

Several empirical settings of the parameters in the *EMPS* model go in line with the overall philosophies of the different storylines. This means in particular, that e.g. several capacity settings, both generation and cross-border transmission, are implemented in accordance with the overall description of the storylines. E.g. in the *Blue* storyline with large-scale, centralized offshore RES-Electricity generation higher cross-border transmission capacities are

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[8] See www.res2020.eu for more details.

[9] See Appendix A.1 for a graphical representation of the biomass price development up to 2050.

implemented in the model than for the remaining storylines. As the major output, *EMPS* delivers a series of wholesale electricity prices per storyline on country-level on an annual basis up to 2050.

2.3 Selection Criteria for Case Studies

2.3.1 Objectives of the Scenario Studies

The most innovative aspect of the analyses made is that they not only determine RES supply / demand balances in a particular region and / or country but also comprehensively study corresponding grid infrastructure integration needs and costs for the optimal integration of renewable energy sources. Additionally, in geographic terms the analysis is not only restricted to the boundaries of a particular country but, in a second step, also determines the (electricity-) balances to / with neighbouring regions and / or countries.

This is also true for the grid infrastructure analysis. The grid infrastructure analysis, furthermore, is not only restricted to the electricity grids but also analyses the role of gas and heat grids in this context and, most important, the interdependencies between the different network infrastructures for an optimal RES deployment in the long-term. Besides the above mentioned major results derived from the regional scenario studies also a variety of other quantitative and qualitative results are extracted.

The following two major considerations form the rational background for selecting and conducting different (regional) case studies:

- The complexity of RES grid infrastructure integration significantly depends on the existing structure of the energy system. Due to the fact that in the different European regions / countries fundamentally different energy systems exist (e.g. in terms of flexibility of the power plant portfolio in the electricity sector, dominance and resource availability / corridors of natural gas in the electricity and heating sector, historically grown structures and dominance of fuels used in the heating sectors, etc.), a representative amount of regional case studies has to be conducted to be able to study several important aspects / dimensions of more efficient RES grid infrastructure integration into future energy systems. However, the number of regional scenario studies has to be limited also in order to avoid (i) redundancy of the major features describing the existing energy systems and RES resource availability and (ii) to run out of time and to deliver the outputs in time.
- Each of the different regional scenario studies is also a comprehensive stand-alone study on RES grid infrastructure integration for the region itself under a variety of different possible future “environments” (i.e. scenarios) in the region up to 2050. In this context, the long-term perspective is important to be able to study possible “structural breaks”[10], on the one hand, and also to consider extremely long lead times of grid infrastructure planning and implementation necessary to absorb large amounts of RES generation, on the other hand. Moreover, the regional scenario studies shall significantly support the development of regional RES grid integration strategies both short- and long-term.

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[10] E.g. phasing in and / or phasing out of new energy technologies and / or energy policies.

Based on the considerations stated above the major objectives of the regional scenario studies can be summarized as follows:

- Contribution *of the region* and the regional energy system and its resources to study the complexity of RES grid infrastructure integration under a variety of different constraints;
- Development of different RES grid integration strategies and recommendations *for the region* up to 2050.

2.3.2 Selection Criteria of the European Regional Scenario Studies

Having in mind the existing energy systems in the European countries and the future potential of renewable energy sources all over Europe[11], the criteria for the selection of the different European regions being representative to get sufficient insight to cover some of the most important cornerstones of interest has finally resulted in three different (regional) case studies: Austria (Alpine / Central Western Europe region), Serbia (Western Balkan region) and Spain (Iberian Peninsula).

The main criteria determining the selection of different regions / countries in the scenario analyses can be summarized as follows:

- Number of regional scenario studies: A critical number of regional scenario studies is necessary in order to cover several representative geographic regions all over Europe.
- Consideration of different status quo (starting points) of renewable integration: There exist considerable differences in the status quo of renewable deployment in different European countries, e.g. compare existing RES deployment in (i) “old” EU15 Member States (partly high RES shares are already implemented) and (ii) “new” EU12 Member States and Balkan Countries (significant RES investment opportunities exist for the future, less financial support instruments for RES implementation at present).
- Different characteristics of the energy systems: The different regional scenario studies describe different determinants, challenges and complexities of RES grid infrastructure integration being also transferable to other European regions and being characterized by similar features and constraints.
- Renewable / environmental policy, energy market maturity and macro-economic aspects: In different European regions significant differences with respect to these different determinants exist. This has to be reflected in the selection of the regional scenario studies, too. There exist fundamental differences e.g. in terms of the political situation in general, environmental consciousness, maturity of the energy markets and also macro-economic developments.

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[11] … as well as in the surroundings of the European Continent as there are e.g. the Atlantic Ocean (wave, tidal and offshore-wind energy) as well as Northern Africa (e.g. concentrated solar power from the Saharan Region, etc.).

2.3.3 Characteristics of the Three European Regions / Countries

The main characteristics of the three European regions/countries which have been subject to comprehensive scenario study analyses[12] are listed below:

- Austria (Central Western Europe Region): Austria has similar characteristics of the energy system like other countries in Central Western Europe (CWE) including significant storage and variability mitigation options due to pumped-hydro energy storage (PHES) power plants. Further on, Austria is a significant electricity hub in Continental Europe (North / South; East / West) with still not utilized potentials for hydro power.
- Serbia (Western Balkan Region): The Western Balkan region is supposed to be part of the European Union in the future. Serbia, like other countries in the region, has a poor energy infrastructure and the energy market liberalisation is still in the process of implementation. The region has significant RES potentials (mainly hydro power), but is lacking in deployment. However, the recently started financial support schemes for renewable energy and the growing energy demand might change this in the future.
- Spain (Iberian Peninsula): Thanks to high RES potentials and financial support, Spain already has large shares of wind and solar (PV and CSP) electricity generation in the system. Due to weak transmission grid interconnectors, the Iberian Peninsula is more or less an isolated electricity market. In the future, the warm climate will lead to a further growing cooling demand and higher summer peak consumption. However, there are still high remaining potentials on wind and solar electricity generation and additionally there is a possibility of RES-Electricity imports from North Africa.

More details about the individual analysed regions and countries are presented in the respective sections in chapter 4 and 5.

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[12] In the project SUSPLAN nine different European regions/countries in total were analysed (see Auer et al., 2010 for a summary of the main results in the different case studies).

3 Methodology / Modelling Approach

3.1 *Analysis of the Electricity Sector*

3.1.1 Analysis of the Austrian and Serbian Electricity System

The "Green Loop" (Sequence of three Models)

In the scenario analyses it is implicitly assumed that in the future the harmonization process of the European energy markets in general, and electricity markets in particular, will be continued. Therefore, electricity market models like *EMPS* – briefly described already in section 2.2.5 – are qualified to determine reference wholesale electricity market price levels in the different regions throughout Europe. Moreover, wholesale electricity market prices are supposed to be the key benchmarks determining the economics and phase-in levels of RES-Electricity generation technologies. Even more, deployment of RES-Electricity generation technologies and its integration into grid infrastructures will also be based on least-cost principles where the best available sites for the utilization of RES-Electricity generation are given priority.

In the regional scenario studies the model '*GreenNet'* – equipped with several features to fulfil this task (see section (ii) in detail) – is applied for determining the least-cost merit order of renewable electricity generation in the different regions and in the different storylines up to 2050. If necessary, the model *GreenNet* is run iteratively with *EMPS* in order to reach consistent, robust and finally converging wholesale electricity market prices on nodal (regional) basis.

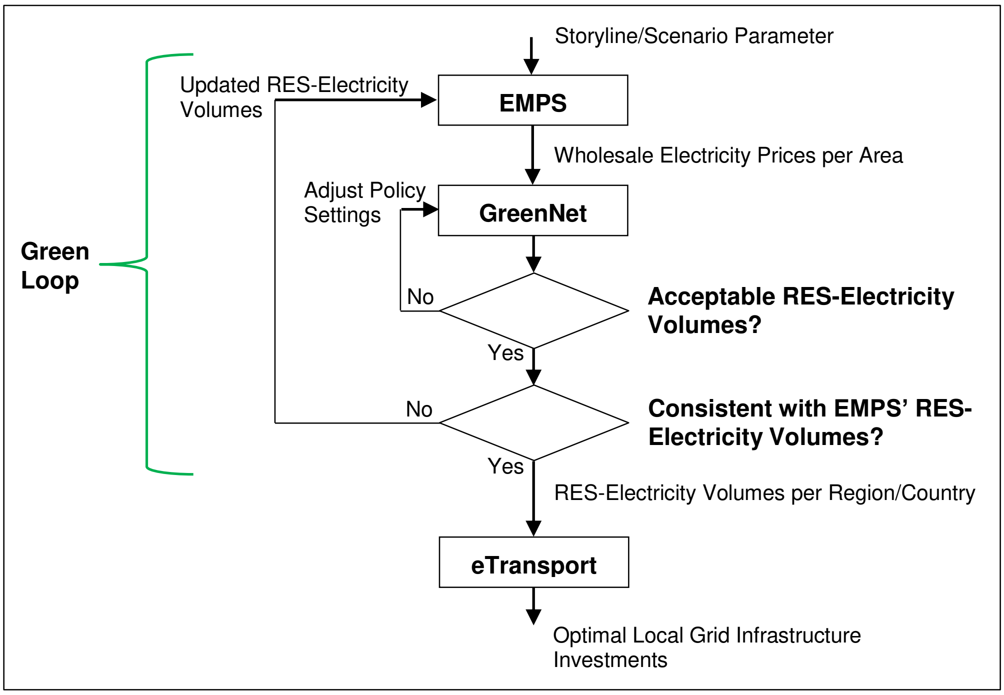

Figure 9: Sequence of model applications in the "*Green Loop*" for the analysis of the electricity sector in Austria and Serbia (Source: own description)

In the next and final step of scenario analyses in a particular region, the spatial dispersion of least-cost renewable electricity generation sites and load centres insight and also outside a region have to be considered, taking into account the possible routes for grid infrastructure implementation. This task can be perfectly covered with the software tool '*eTransport'* (see section (iii) in detail); a multi-grid infrastructure investment modelling tool qualified to combine several possible generation and load patterns with different grid infrastructures.

The sequence of model application *(EMPS → GreenNet → eTransport)* presented above perfectly describes the regional scenario analyses process. For this sequence of model applications the term "*Green Loop*" has been established, also referring to the possibility of iterative applications of this model sequence in case fine tuning of wholesale electricity market price determination and RES-Electricity deployment calculation is necessary and / or desirable (see Figure 9).

(i) EMPS Model – Calculation of European Wholesale Electricity Prices

As already said before, the *EMPS* model is a socio-economic energy system model for electricity that can handle systems with large shares of intermittent electricity generation. Basically it is a stochastic model for optimization and simulation of large hydro-thermal power systems. The model is able to calculate a minimum cost strategy for operation of an energy system with intermittent sources, long- and short-term storage options and conventional electricity generation. Intermittent renewable generation[13] is modelled based on 70 years of hourly climate data and with different series for the different RES sources.

In this application of the *EMPS* model each EU 27+ country is considered as a distinct power market with import / export capacities to the neighbouring areas (direct current load flow). Within each country the energy balance is simulated based on a mix of fixed demand and price dependent demand which is balanced by the domestic generation assets but also considering import / export capacities.

The wholesale electricity market price in each country strongly depends on the transmission capacities to the surrounding countries. To ensure that the price differences do not become unrealistically high as the four different storylines develop, it is necessary to adjust the import / export capacities between the countries. The approach toward transmission capacities in the *EMPS* and "*Green Loop*" calculation is based on heuristic transmission expansion. If wholesale electricity price differences between the markets become too large, the capacity between them is increased.

The major result derived with *EMPS* is the wholesale electricity price per region / country, which is then used as input parameter for its "*successor*" model *GreenNet*. Further results available from the *EMPS* calculations are generation by type, consumption in each country, storage utilization, exchange on transmission lines, etc.[14]

For further insights into the *EMPS* model it is referred to http://www.sintef.no/home/SINTEF-Energy-Research/Project-work/Hydro-thermal-operation-and-expansion-planning/EMPS/.

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[13] E.g. solar, onshore wind, offshore wind, wave power and hydro power

[14] Expansion planning features of the *EMPS* model are not applied in the "*Green Loop*" as they are based on purely economic signals. Elements such as RES support instruments (e.g. feed-in tariffs, barriers, etc.) are strength of *GreenNet* modelling. Therefore, they are not considered in the *EMPS* model.

(ii) GreenNet Model – Least Cost RES-Electricity Deployment

The basic principles of the modelling approach of the least-cost RES-Electricity deployment simulation tool *GreenNet* are briefly described in the following.

Firstly, the *GreenNet* model is deriving the dynamic RES-Electricity potentials in a particular country in a particular year by determining the additional long-term potential up to the year 2050[15]. The additional long-term potential is the maximal additional achievable potential for RES implementation assuming that several existing barriers can be overcome and all driving forces are active (cf. Figure 10). Then the individual 2050 technical potentials of each of the RES-Electricity generation technologies in a region / country are "*downscaled*" to a dynamic RES-Electricity potential for a particular year (i.e. considering several kinds of barriers and upper limits for annual integration).

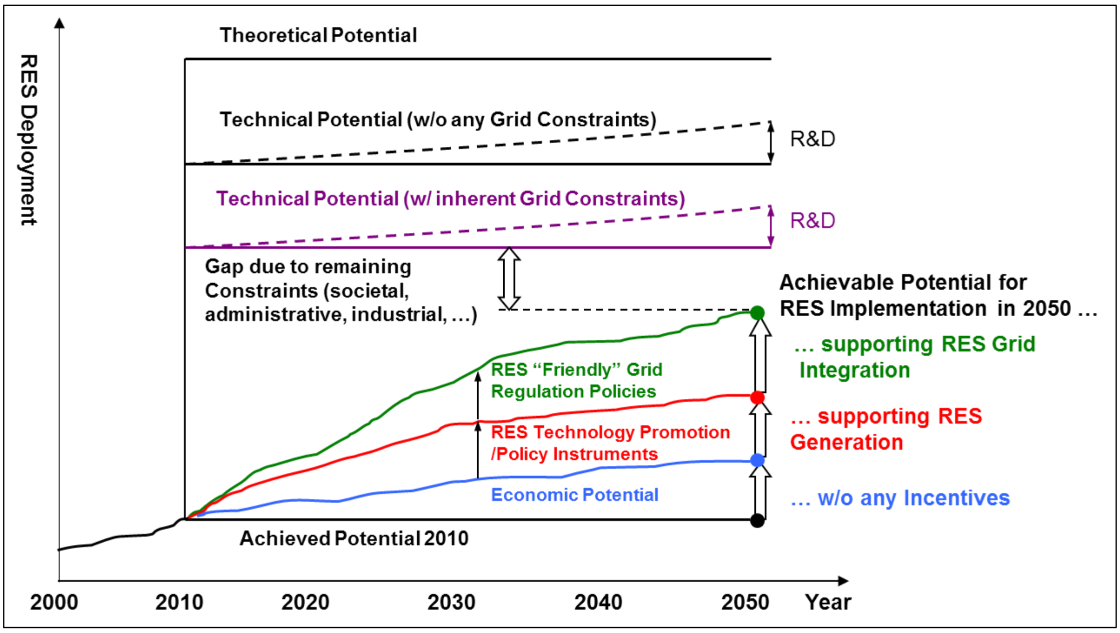

Figure 10: Methodology for the definition of the different RES-Electricity potentials (based on Resch et al., 2003)

In a next step, the "*trade-off*" calculation of RES-Electricity potentials / costs and the exogenously determined wholesale electricity market price (delivered from the *EMPS* model) is executed. In this context it is important to note that in the *GreenNet* model RES-Electricity costs can be considered both with and without financial support and promotion instruments like feed-in tariffs, tradable green certificates, etc.

The major results of *GreenNet* simulation runs (to be used as an input for the *eTransport* multi-grid infrastructure investment tool) are time series of RES-Electricity deployment (on technology level) in terms of installed RES-Electricity capacities and annual RES-Electricity generation in a particular region up to the year 2050.

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[15] For the long-term analysis the original *GreenNet* model (see http://www.greennet-europe.org/), which has a time scope of 2005 to 2030, was updated accordingly.

For further insights into the *GreenNet* model it is referred to http://www.greennet-europe.org/ notably the work-package 8-report (Huber et al., 2004b) with the analytical framework of the *GreenNet* software.

(iii) eTransport Model – Multi-Grid Infrastructure Investment Tool

The main objective of the *eTransport* model is to optimize investments in multi-grid infrastructures (electricity, heat and gas grids) and its conversion components over a long-term planning horizon and, simultaneously, to connect available generation technologies *("resources")* with different load *("end-uses")* in a way that end-uses are met in the economically and environmentally best way. As part of the investment analysis, however, the *eTransport* model also optimizes diurnal operation for different periods of the year for each alternative system design.

eTransport is separated internally into two different models, an operational model (energy system model) and an investment model. The operational model determines the minimal operating costs for a given energy system to satisfy predefined energy demands. Different *segments* representing different periods in a year (e.g. summer / winter, work days / weekend), different *states* (i.e. design / expansion of the energy system) and different *periods* (i.e. list of years) can be defined in order to incorporate changes in demand profiles, used technologies, price levels etc. in the calculated annual operating costs (cf. flowchart in Figure 11).

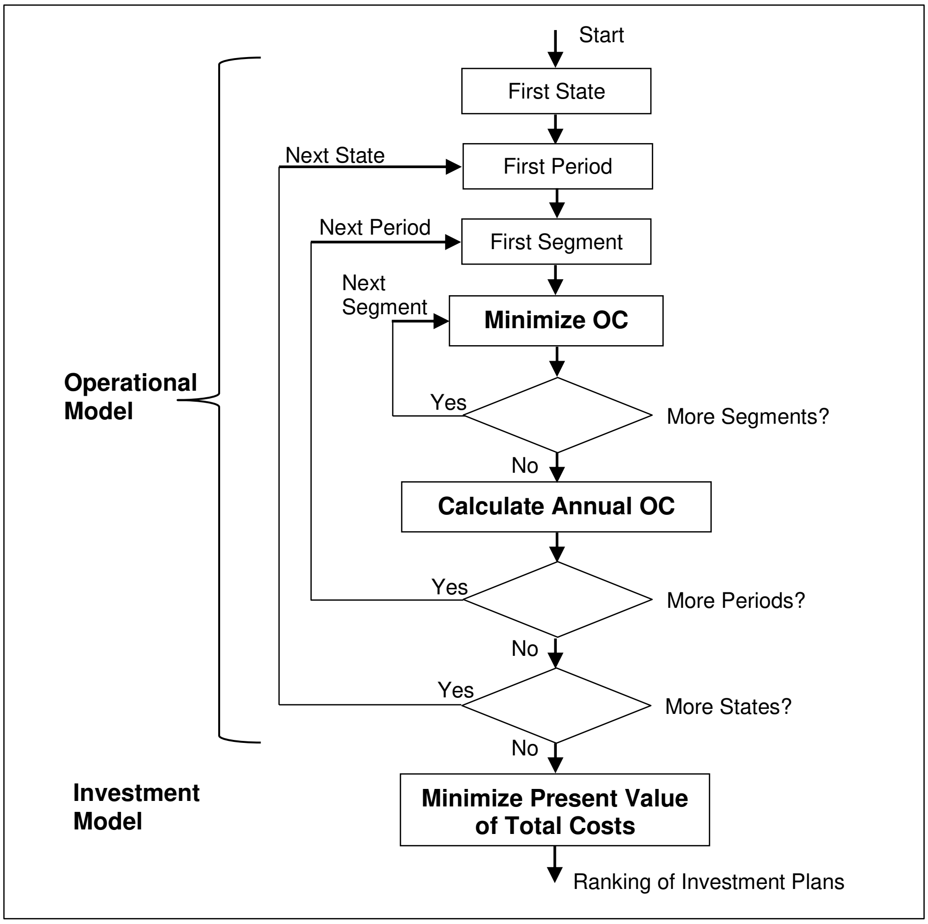

Figure 11: Flowchart of the *eTransport* model (based on Bakken et al., 2007)

In a next step, the investment model finds the optimal set of investments during the analysed period by minimising the discounted present value of all costs, i.e. pre-calculated annual operating costs (from the operational model) plus the investment costs for the different (predefined) projects minus the rest value of investments (cf. Equation 1, Bakken et al., 2004).

Equation 1: $$\min\left\{\sum_{t\in T}\delta_t * \left(t^{step} * c_t^{ope} + c_t^{inv}\right) - \delta_{t^{end}} * \Phi\right\}$$

$\delta_t, \delta_{t^{end}}$ … Discounting factors
t^{step} … Number of years where c_t^{ope} is valid
c_t^{ope} … Optimal operating cost for a given state and year
c_t^{inv} … Investment cost for a given state
Φ … Rest value of investment at end of optimization period

Finally, the model provides a ranking of possible expansion / investment plans with the lowest total costs and for each plan the investments that are realised in different periods, the net present value of all costs, annual operating costs for different periods, etc.

In Figure 12 the model set-up is outlined, showing how the *eTransport* model incorporates the results from the electricity sector from the *GreenNet* modelling analyses. In detail, the time series of annual available RES-Electricity generation sites identified by the *GreenNet* model (i.e. in terms of installed capacities, annual electricity generation and also generation cost per technology) are treated in *eTransport* the same way like any other conventional power plant for electricity generation (considering, however, the individual generation characteristics like e.g. variability / intermittency) and / or purchases from the wholesale electricity market. The *eTransport* model is scaled separately for each of the regional scenario analysis in the four different storylines.

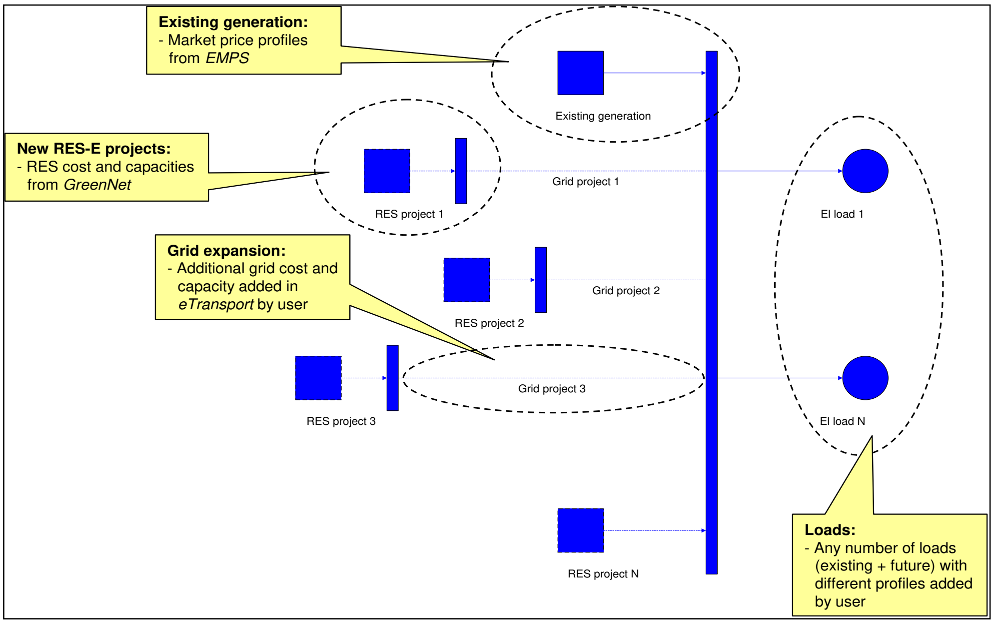

Figure 12: Incorporation of *GreenNet* time series results on RES-Electricity deployment into the *eTransport* model set-up (Source: Auer et al., 2009)

For further insights into the *eTransport* model it is referred to http://www.sintef.no/home/SINTEF-Energy-Research/Project-work/eTransport-/.

3.1.2 Analysis of the Spanish Electricity System

In the Spanish case study analysis, which was performed by the *Universidad Pontificia Comillas* in the *SUSPLAN* project, the electricity generation mix up to 2050 and the associate grid infrastructure investments in the four different storylines were determined in three steps. First, the optimal expansion of the Spanish electricity generation capacity up to 2050 was determined for the four different storylines. Then, for each storyline a detailed analysis of the power system operation was performed. For these two tasks, two different electricity models were sequentially used: a long term generation expansion model and a medium-term system operational model. Finally, the regional grid infrastructure investments were computed based on the installed power plant capacities and the overall power system operation[16].

As already said before, the analysis of the Spanish electricity system was not performed by the author himself, but, in order to draw overall results and to make comparisons between different electricity systems, the modelling results of the Spanish system are also included in this paper. For further insights into the Spanish modelling approach it is referred to Frías et al., 2010.

3.1.3 Analysis of the European Electricity Market Regions

The modelling approach for the analysis of the electricity sector described beforehand (i.e. the Green Loop and the methodology for the Spanish case study) provide results for RES-Electricity generation / installed capacities and corresponding transmission grid investment costs / needs on country- and on annual level. As a complementary analysis which shows also interdependencies of neighbouring regions / countries and the importance of bulk electricity storage technologies (EST, i.e. mainly PHES and CAES) for integrating large amounts of variable RES-Electricity, on the one hand, and mitigating their effects, on the other hand, (residual) electricity load duration curves are derived and analysed for so-called "*European electricity market regions*" (EEMR) on an hourly basis for the years 2030 and 2050[17]. For this, the assessment of the geographical allocation of future potentials for PHES in Europe was a precondition.

For deriving the residual electricity load duration curves of the different EEMR in the years 2030 and 2050 and considering the operation of the PHES system of the respective region, a linear optimization algorithm was established in GAMS (General Algebraic Modeling System)[18]. The task and constraints of this algorithm are given in the respective section below.

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[16] For more information about the modelling approach see Frías et al., 2010.

[17] The derivation of the residual load curve is described with the aid of an example in section 4.4.1 in detail.

[18] For more information about GAMS see http://www.gams.com/.

Geographical Allocation of Future Potentials for bulk EST in Europe

The geographical allocation of future potentials for bulk EST in Europe is estimated based on the most relevant work and studies existing 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, 2011a)
- National renewable energy action plans (NREAP) (Beurskens et al., 2011)
- Green-X database[6]
- JRC – PHES: potential for transformation from single dams (JRC, 2012)

Further on, an internet research for gathering data of utilities in the different countries was carried out in order to get more detailed information of local (P)HES systems.

The result of this potential estimation for bulk EST in Europe is shown in Figure 13.

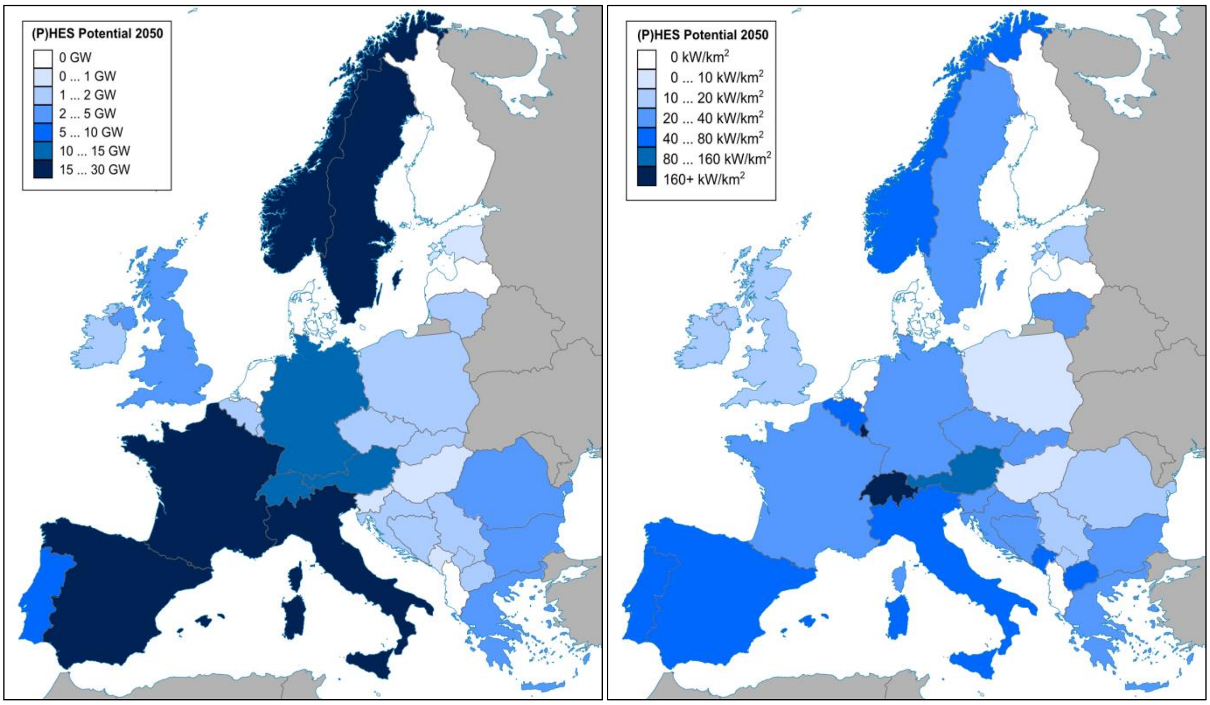

Figure 13: (P)HES potential in Europe until the year 2050: Power capacity per country [GW] (left) and power capacity per land area per country [kW/km^2] (right) (Data source: see text above)[19]

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 13 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

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[19] See Appendix A.3 for input data tables.

efficiencies and to eliminate the need for using additional fossil fuels (i.e. advanced adiabatic CAES)[20].

Further on, it is important to note that the majority of the used sources for the estimation of the European (P)HES potential only provide scenario / projection figures including currently operating, planned / projected (P)HES and (P)HES systems under construction. Therefore, the potential figures in our analysis represent rather economical than technical potential figures for (P)HES. The actual technical potential of (P)HES systems in the European countries might be higher[21].

Figure 13 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[22].

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 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, 2011a).

Clustering of European Countries into Nine European Electricity Market Regions

Due to physical constraints in the European (cross-border) 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 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

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[20] See Zach et al., 2012 for more details.

[21] Currently, a joint study of JRC and University College Cork (UCC) assesses the European potential for PHES, see http://ec.europa.eu/dgs/jrc/index.cfm?id=1410&obj_id=14710&dt_code=NWS&lang=en.

[22] No data is available for Albania.

- 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 14.

Figure 14: Clustering of countries to nine different European electricity market regions

Integration of Surplus RES-Electricity Generation with PHES systems

Bulk energy storage technologies are expected to be one of the key enabling technologies for the integration of large amounts of variable RES-Electricity generation. In particular, the ability to quickly discharge large amounts of stored electricity and to store surplus RES-Electricity generation especially in off-peak times can mitigate many challenges which arise with high shares of variable RES-Electricity generation in the electricity system.

Therefore, after derivation of the residual load curves in the three analysed EEMR (i.e. CWE, Western Balkan and Iberian Peninsula) for the years 2030 and 2050 the capability of PHES systems to integrate surplus RES-Electricity generation and provide peak-load power in the regions was analysed in a subsequent step. For this, the individual residual load curves were taken as input for a small linear optimization algorithm, which was written in GAMS[23]. The task of this algorithm is the maximization of the revenue of PHES systems in the EEMR:

Equation 2: $\max\left\{\sum_{t\in T} RL(t) * \left(P_{Turb}(t) - P_{Pump}(t)\right)\right\}$

$RL(t)$ … Residual load in hour t
$P_{Turb}(t)$ … Turbine power of PHES system in hour t
$P_{Pump}(t)$ … Pumping power of PHES system in hour t

Since the actual hourly electricity prices are not available in the year 2030 and 2050, the values of the hourly residual load values are taken as proportional indicator for the future electricity price, i.e. high residual load values are equivalent to high electricity prices. Especially surplus RES-Electricity generation might be available for low cost or even negative prices. The revenue is optimized under the following constraints:

Equation 3: $for\ RL(t) \geq 0$: $RL(t) - P_{Turb}(t) \geq 0\ \ and\ \ P_{Pump}(t) \leq RL(t)$

Equation 4: $RL(t) - P_{Turb}(t) + P_{Pump}(t) \leq RL_{max} - P_{max\,Turb}$

Equation 5: $for\ RL_{min} + P_{max\,Pump} \leq 0$: $RL(t) - P_{Turb}(t) + P_{Pump}(t) \geq RL_{min} + P_{max\,Pump}$

RL_{max}, RL_{min} … Maximum and minimum residual load
$P_{maxTurb}$ … Maximum turbine power of PHES system
$P_{maxPump}$ … Maximum pumping power of PHES system

In case of a positive residual load the constraints in Equation 3 assure that, on the one hand, the PHES system does not turbinate beyond zero (i.e. no negative residual load through turbining) and, on the other hand, limit the pumping power to the residual load in order to set the right price signals for the optimization[24]. Equation 4 and Equation 5 assure that the positive and also negative peak-loads are maximally reduced by the PHES system. With these constraints, the optimization algorithm also guarantees a maximal integration of excess RES-Electricity generation in the EEMR.

Further constraints applied in the algorithm are typical limits to the storage capacity of the PHES system:

- 80% cycle-efficiency
- Maximum energy storage capacity was defined per EEMR
- Start- and end-value of stored energy must be the same
- Start-value for the energy stored is set to half of the maximum energy storage capacity

Further on, all PHES systems of an EEMR are modelled as one big PHES system with symmetrical upper and lower storage reservoirs and no natural inflow / drainage. The open source solver "*OSICPLEX*" was used for executing the optimization.

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[23] For the complete GAMS-code see Appendix A.10.

[24] Without this constraint the algorithm would use full pumping power also in case of a very low residual load - leading to a considerable increase in the residual load and therefore electricity prices. The constraint limits this load and price increase in order to reflect the market power of the PHES system.

3.2 Analysis of the Heat / Gas Sector

3.2.1 Analysis of the Austrian and Serbian Heat / Gas Sector

An extended version of the *eTransport* model was also used for the analysis of the heat / gas sector in the Austrian and Serbian case. Figure 15 presents this extension of the *eTransport* model on aggregated level, indicating how different loads can be met and served by alternative network infrastructure routes: electricity, heat and / or gas grids.

In general, when constructing a particular *eTransport* case, a large number of different generation technologies, grid infrastructure elements and components as well as loads can be connected. Basically, it is up to the user to decide the level of aggregation and the emphasis of the different grid infrastructure elements and components in the model setup in a particular case in the different scenario studies.

For a further example of a setup of an *eTransport* analysis in the heat / gas sector (namely in the Austrian case) it is referred to the Appendix A.4.

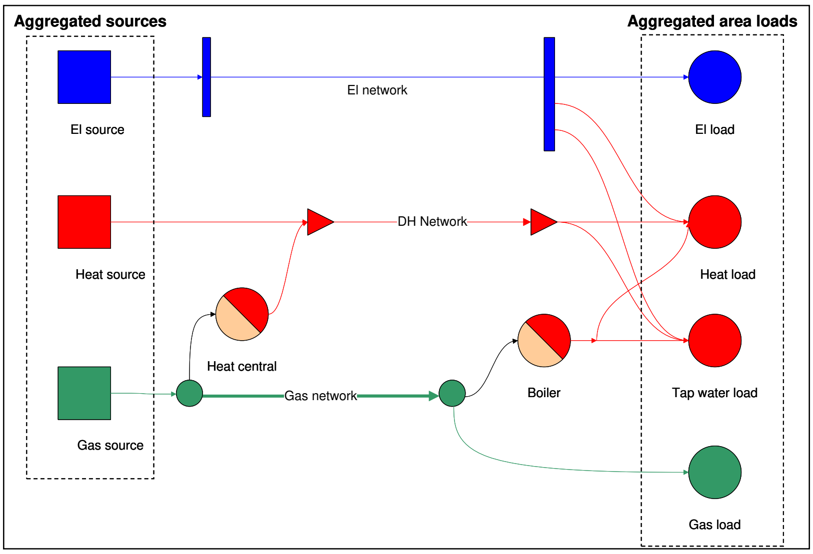

Figure 15: Basic elements of the *eTransport* model on aggregated level (resources, grid infrastructure elements / components, loads)

3.2.2 Analysis of the Spanish Heat / Gas System

Also the heat / gas system analysis of the Spanish case study was performed by the *Universidad Pontificia Comillas* (see Frías et al., 2010) within the *SUSPLAN* project. In particular, the methodology is focussed on the estimation of the future gas infrastructures needs. For this, an estimation of the gas demand for the period 2020 to 2050 was conducted first and followed by a calculation of the needs of additional gas infrastructure reinforcements (taking into account gas demand and existing gas network design criteria).

In particular, peak gas consumption is of interest for the estimation of future gas infrastructure needs. Usually, peak gas demand in Spain occurs in winter due to use of gas for heating purposes and electricity generation of gas-fired power plants, (especially CCGTs) to meet peak electricity demand. Therefore, the main objectives of transmission gas infrastructure planning can be summarized as follows:

- Supply (winter) gas peak demand;
- N–1 criterion: In case of failure of one important gas supplier (also including interconnections) the system must be able to supply gas demand in a winter working day, and gas demand of 90% of the CCGT power plants needed to cover the electricity demand;
- An overcapacity of 10% to cover unexpected gas demand increases.

Finally, the gas pipelines should be designed to supply the gas demand, minimizing the distance between supply and demand points, and to guarantee a secure operation.

For further details of the Spanish heat / gas system analysis approach it is referred to Frías et al., 2010.

4 Selected Case Study Results from the Analysis of the Electricity Sector in the Blue Storyline

Out of the four different analysed storylines, the *Blue* storyline is selected for representing the analysis in the electricity sector. The main reasons for choosing *Blue* over the other storylines is that it is the most "*tricky*" future for electricity systems: there is high demand growth but low public acceptance for decentralised RES-deployment (e.g. PV) and DSM. Additionally, high feed-in of variable and centralised RES-Electricity systems (e.g. offshore wind, CSP) leads to high surplus electricity generation occasionally. Therefore, PHES systems (the main technology for storing large amounts of electricity in the *Blue* storyline) have a crucial role in balancing the electricity system and storing excess RES-Electricity in *Blue*, which qualifies this storyline for the analysis of the European Electricity Market Regions (EEMR; see section 4.4).

The results of the grid integration analysis of RES-Electricity are presented country wise (i.e. Austria, Serbia and Spain) in the following sections. For each country the status quo and the short-term development of the electricity generation system as well as the status quo of the transmission grid system are briefly summarized before presenting the respective results of the analysis (i.e. RES-Electricity deployment and corresponding transmission grid infrastructure needs and costs in the *Blue* storyline).

4.1 Austria

4.1.1 Status Quo of the Austrian Electricity Generation System

Hydropower generation covered approximately 57% of Austrian electricity generation in the year 2011. It is the main electricity generation technology in Austria with an installed capacity of about 13,200 MW (see Table 1). In the past, Austria has developed a capacity of about 7,800 MW on (P)HES due to its geographical characteristics in the Alpine region. About half of this installed capacity for electricity generation (i.e. about 3.9 GW) is allocated to PHES systems. The pumping capacity of the Austrian PHES systems was about 2.9 GW in the year 2011.

The key policy instrument at the national level to support RES-Electricity technologies is the Austrian Green Electricity Act ("Ökostromgesetz", AGEA). After its adoption in 2002 and several following amendments, feed-in tariffs caused a particularly strong deployment of wind energy, biomass and biogas. However, with an actual installed wind capacity of around 1,100 MW, wind energy only accounts for about 3% of the total Austrian electricity generation in the year 2011. In total (including HPPs), RES-Electricity had a share of about 65% on total electricity generation in Austria in the year 2011.

The domestic electricity consumption in Austria in the year 2011 was about 74 TWh, including 5 TWh for pumping purposes in Austrian PHES systems and 2 TWh own consumption of power plants. In general, Austria is a net importer of electricity. In the year 2011 the net import / export balance was about 8 TWh (imports).

Table 1: Electricity generation system in Austria in the year 2011 (Source: E-Control, 2012)

Electricity Generation System in Austria 2011						
Power Plant Technologies			Count	Power Capacity [MW]	Electricity Generation [GWh]	Share on Total Electricity Generation
Hydro Power Plants (HPP)	Run-of-River	> 10 MW	90	4,433	21,024	31.95%
		< 10 MW	601	782	4,252	6.46%
	(P)HES	> 10 MW	67	7,615	11,996	18.23%
		< 10 MW	44	150	429	0.65%
	Other Small-scale HPP		1,869	221		
	Sum HPP		**2,671**	**13,200**	**37,701**	**57.29%**
Thermal Power Plants (TPP)	Fossil Fuels and Derivatives	Coal	4	1,171	5,315	8.08%
		Derivatives	7	444	1,931	2.93%
		Oil-Derivatives	11	362	1,179	1.79%
		Natural Gas	64	5,102	11,556	17.56%
		Sum	86	7,079	19,982	30.36%
	Biomass and Biogas		107	508	2,694	4.09%
	Co-Firing		10	497	2,086	3.17%
	Other TPP		380	166	1,071	1.63%
	Sum TPP		**583**	**8,249**	**25,832**	**39.25%**
	(of which CHP-units)		(185)	(6,599)	(21,063)	(32.00%)
RES-E	Wind[25]		656	1,084	1,934	2.94%
	Photovoltaics[26]		n.a.	187	174	0.26%
	Other RES-E		10,375	72		
	Sum RES-E		**11,031**	**1,343**	**2,108**	**3.20%**
Other Electricity Generation			n.a.	n.a.	170	0.26%
TOTAL			**14,285**	**22,793**	**65,812**	**100.00%**

4.1.2 Short-term Development of the Austrian Electricity Generation System

Austria still has a development potential for (small-scale) HPP and PHES – in combination with revitalization / repowering measures of existing power plants. Actually wind power is already strongly developed due to good natural-space conditions in particular in the eastern part of Austria (Lower Austria, Vienna and Burgenland). Under consideration of the future transmission grid situation (see next section) further development potential also exists. PV and geothermal energy are currently of minor importance in Austria. However, with the further development of building-integrated PV systems, PV could also play a significant role in the future.

Table 2 presents the estimation of total contribution (installed capacity, gross electricity generation) expected from each RES-Electricity technology in Austria to meet the binding EU-2020 targets (EU Directive 2009/28/EC) according to the National Renewable Energy Action Plan of Austria (NREAP-AT). Further on, also the gross final electricity demand is given in Table 2 for the two different scenarios defined in NREAP-AT: a reference and an

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[25] Data source for wind energy: IG Windkraft, 2012.

[26] Data source for PV: Biermayr et al., 2012.

efficiency scenario. The resulting share of RES-Electricity generation on final consumption in the year 2020 is about 67.6% for the reference scenario and 70.6% for the efficiency scenario respectively.

Table 2: Development of RES-Electricity according to the NREAP-AT (Source: Karner et al., 2010)

Development of RES-E Technologies in Austria (NREAP)					
RES-E Technology		**2005**	**2010**	**2015**	**2020**
HPP	[MW]	7,907	8,235	8,423	8,997
	[GWh]	37,125	38,542	39,423	42,112
Pumping (PHES)	[MW]	3,929	4,285	4,285	4,285
	[GWh]	2,738	2,732	2,732	2,732
Geothermal	[MW]	1	1	1	1
	[GWh]	2	2	2	2
PV	[MW]	22	90	179	322
	[GWh]	21	85	170	306
Wind	[MW]	694	1,011	1,951	2,578
	[GWh]	1,343	2,034	3,780	4,811
Biomass	[MW]	976	1,211	1,228	1,281
	[GWh]	2,823	4,720	4,826	5,147
Renewables in Electricity	**[MW]**	**9,600**	**10,547**	**11,781**	**13,179**
	[GWh]	**41,314**	**45,383**	**48,200**	**52,377**
Gross Final Electricity Consumption	**Reference**	**66,581**	**65,523**	**70,838**	**77,525**
	Efficiency	**66,581**	**65,523**	**67,651**	**74,164**

However, the new Austrian RES legislation changes some of the RES deployment ambitions up to 2015 and 2020 for some of the RES technologies, notably PV generation. A main difference in the amendment of the AGEA 2012 (Ökostromgesetz – Novelle 2012, BGBl I Nr. 75/2011) is that the PV deployment target is significantly increased to an additional 500 MW on PV capacity from 2010 until 2015 (compared to 17 MW previously) and 2 GW until 2020 respectively. Table 3 summarizes the targets of additional RES-E deployment until 2015/2020 according to the AGEA 2012.

Table 3: Targets of additional RES-E deployment according to the Austrian Green Electricity Act 2012 (Source: OESG, 2011)

RES-E Technology		2015	2020
HPP	[MW]	700	1,000
	[GWh]	3,500	4,000
PV	[MW]	500	1,200
	[GWh]	500	1,200
Wind	[MW]	700	2,000
	[GWh]	1,500	4,000
Biomass & Biogas	[MW]	100	200
	[GWh]	600	1,300
Additional RES-E	**[MW]**	**2,000**	**4,400**
	[GWh]	**6,100**	**10,500**

4.1.3 Status Quo of the Austrian Transmission Grid System

Since 2012 the whole Austrian transmission grid system is operated by the Austrian Power Grid AG (APG) and is divided into three voltage levels: 380 kV, 220 kV and 110 kV.

The Austrian transmission grid system is characterised by a ring structure (see Figure 16). After the so-called "*Steiermarkleitung*" has taken up operation in mid-2009, the gap of the Austrian 380-kV-ring in the eastern part of Austria has been closed. But still weak spots remain in the western transmission grid areas; particularly the north-south connection St. Peter–Salzach–Tauern ("*Salzburgleitung*"), the lines to Germany and the Zell / Ziller transformer. Furthermore, the Lienz–Soverzene line represents a structural congestion in the southern part of Austria, which at present can only be managed by different congestion management measures like the implementation of phase-shifting transformers.

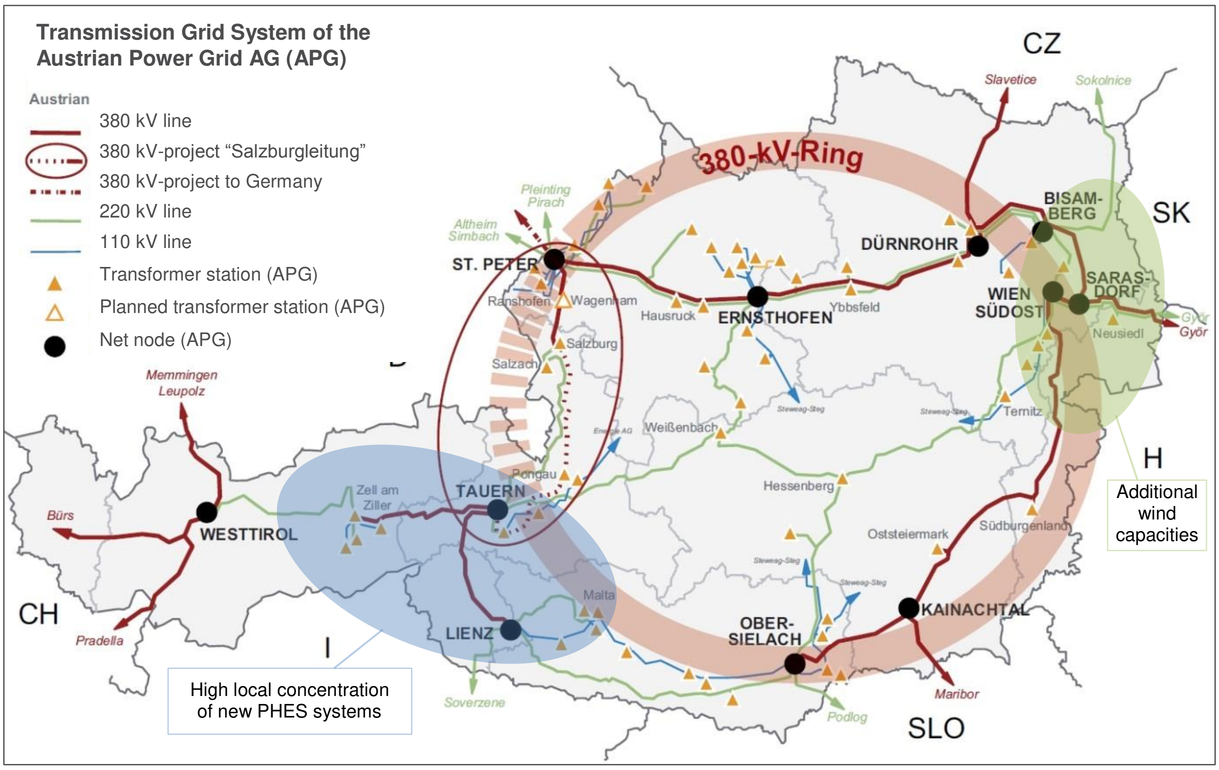

Figure 16: Status quo of the Austrian electricity transmission grid in the year 2011
(Source: APG, 2011)

An important driver for further transmission investments is the implementation of the still unexploited RES-Electricity generation potential in Austria. The two major candidates of RES-Electricity generation technologies expecting significant investments into transmission capacities are (P)HES, on the one hand, and wind power plants, on the other hand (cf. Figure 16):

- PHES systems have been playing an important role already in the last decades due to the fact that they guarantee a high degree of flexibility of the electricity systems not only in Austria but also in the neighbouring countries (e.g. economically attractive "peak-base" exchange contracts with Germany). In the future, the provision of flexible reserve capacities and balancing power demanded by large-scale onshore and offshore wind integration into the Central European electricity systems is expected to enable further attractive business opportunities for additional PHES capacities.

- The most attractive Austrian wind power plants already in operation (and also still not exploited wind potentials) are largely located in the eastern part of the country ("*Parndorfer Platte*"), flexible PHES potentials in the western part ("*Alps*") and, last but not least, there is a lack of sufficient transmission capacities between these two areas. Therefore, incentives to further increase "east-west" transmission capacities in Austria are supposed to be evident.

In the near future, according to "*APG Masterplan 2020*" (APG, 2011), the latest version of the official 10 years generation and transmission adequacy forecast of the Austrian TSO APG[27], up to 5,000 MW of new PHES installations are envisaged up to 2020. Moreover, according to "*APG Masterplan 2020*" also significant investments into the Austrian transmission grid are planned within the footprint of APG in the upcoming years (closure of the so-called "*Austrian-Ring*" up to year 2020 as well as on the different interconnectors to the neighbouring countries). This is also based on the expectation that Austria's high shares and still unexploited future potentials on PHES can be better connected with the high wind potentials in Northern Europe and the high solar-CSP potentials in Southern Europe. The strategic development of the Austrian transmission grid, therefore, is a precondition to enable this.

In terms of the topography of the Austrian transmission grid this means that – compared to the status quo in 2011 (see Figure 16) – the missing transmission links "north-south / south-east" and "east-west" need to be closed. Moreover, this means that up to 2020 the so-called "Austrian Ring" shall be finally implemented

4.1.4 Analysis of the RES-Electricity Deployment in the Blue Storyline for Austria

Main Considerations for the Austrian Case Study in the Different Storylines

Compared to *Red* and *Yellow*, the faster technology development (i.e. more efficient way to use energy) in *Blue* and *Green* is counteracted by a higher level of electrical vehicles and new energy services / appliances. Therefore, for future electricity demand development two different paths are assumed:

- For *Yellow* and *Green* an annual electricity demand increase of 1% until 2030 and 0.8% until 2050 is used.
- In *Red* and *Blue* a higher annual electricity demand increase is used, 1.2% until 2030 and 1.1% until 2050.

Results on RES-Electricity Deployment in Austria from 2010–2050 in the Blue Storyline

In the *Blue* storyline the fast technological development in combination with "top-down" drivers like ambitious RES policies and subsidies lead to fast expansion of RES-Electricity

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[27] An updated version of the "*APG Masterplan*" is due in 2014.

generation, even though the consumer's ambition is low in this storyline. Figure 17 shows the result of *GreenNet* modelling for *Blue* in Austria from 2010 to 2050[28]. It can be seen that electricity generation of newly installed PV (with about +16 TWh/yr in 2050 compared to 2010) and HPP capacities (run-of-river and (P)HES, about +15 TWh/yr in 2050) are the major contributors to RES-Electricity increase in Austria in the *Blue* storyline. The calculated wholesale electricity market price (from *EMPS*) in the *Blue* storyline is at a high level in 2030 (about 130 €/MWh), but then slightly decreases due to the higher shares of RES-Electricity generation in the European system in general to about 110 €/MWh in 2050.

When studying the electricity generation portfolio in Figure 17 in the Blue storyline, it can be seen that generation of newly installed RES-Electricity capacities can cope with the high gross electricity demand increase. The "*gap*" between gross electricity demand and available RES-Electricity generation in Austria in the *Blue* storyline increases until 2030 because of rather low increase of RES-E capacities. From 2030 on, the *gap* decreases again from about 10 to 7 TWh/yr (due to large growth of PV generation).

In *Blue*, a RES share (on gross electricity consumption) of about 78% can be achieved in Austria in the year 2050.

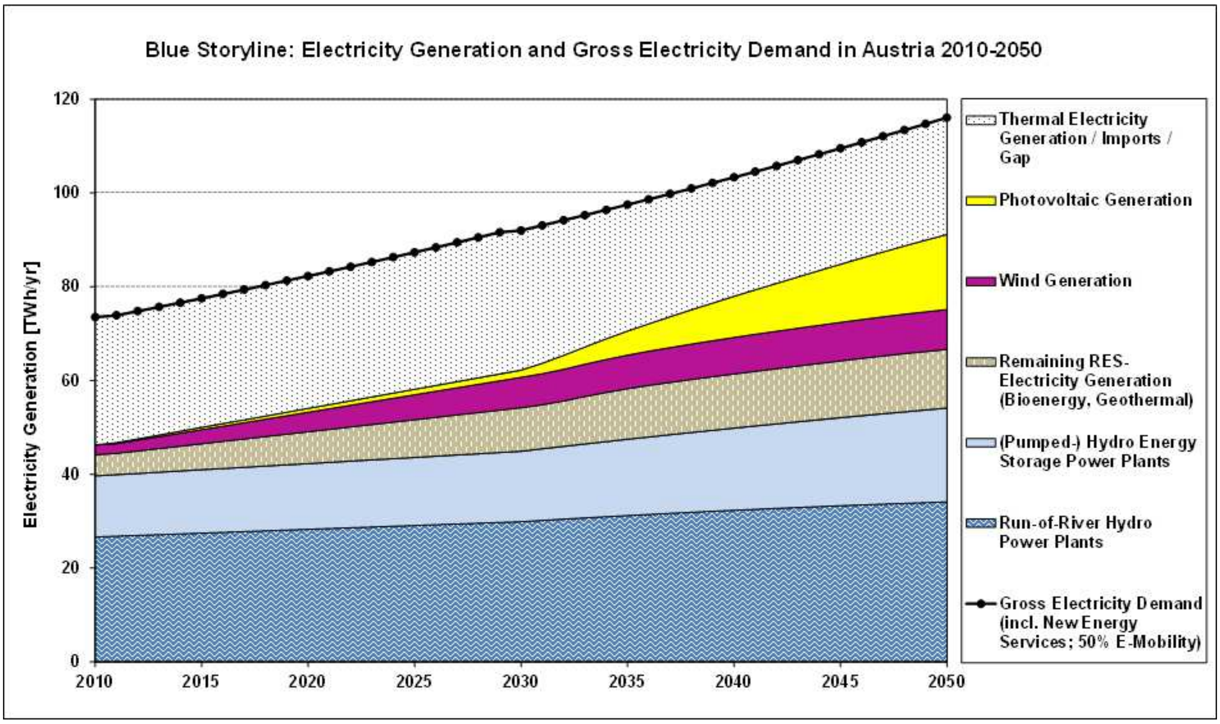

Figure 17: Electricity generation portfolio and gross electricity demand in Austria from 2010 to 2050 in the *Blue* storyline (Source: own calculations)

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[28] See Appendix A.5 for the RES-Electricity deployment results of the remaining storylines for Austria.

4.1.5 Analysis of the Electricity Grid Infrastructure Needs and Costs in Austria

Main Considerations for the Austrian Case Study

One of the major drivers for Austrian transmission grid expansion from 2010 until 2025 / 2030 is the integration of still unexploited RES-Electricity generation potentials, especially (P)HES potentials in the western part of Austria and wind energy in the eastern part of the country. Therefore, investment needs into the Austrian transmission grid from 2030 to 2050 have been analysed based on the needs and necessities to further integrate remaining RES-Electricity potentials.

As can be seen in the results of RES-Electricity deployment portfolios in Austria up to 2050 in the four different storylines in chapter 4.1.4, large amounts of Austria's RES-Electricity generation potentials are expected to be already developed until the year 2030. The only remaining major RES-Electricity potentials will be new (P)HES and PV installations. Wind generation can only be expanded by repowering measures of existing systems, since the most attractive sites will be already taken in 2030.

Since PV is a distributed generation technology and not connected on transmission grid level, in the following analyses this RES-Electricity generation technology (as well as several others connected on distribution grid level) are not taken into consideration. Moreover, only the transmission grid costs for the integration of new (P)HES and wind have been analysed in this regional grid infrastructure case study for Austria.

The following results on grid infrastructure needs and costs for RES-Electricity integration in Austria in the four different storylines are based on the analytical approach already described in section 3.1.1 (see also the respective section 4.2.5 of the Serbian case for more details of the analysis). In addition to the existing transmission grid infrastructure, missing transmission grid upgrades, extensions and routes needed to further integrate the remaining RES-Electricity potentials until 2050 were estimated based on the geographic location of the RES-Electricity potentials. In detail, the residual wind and HPP potentials were located and their distances to the existing transmission grid and / or the length of the transmission grid which need an upgrade / extension were evaluated and integrated in the *eTransport* model. These new investments were implemented with specific transmission grid cost of 2.5 M€/km (average costs for HVAC underground cable, cited from the project "*REALISEGRID*", Rüberg et al., 2010) to be able to quantify the needs and costs for the Austrian transmission grid caused by RES-Electricity integration.

In addition, investment needs for closing the 380 kV *"Austrian Ring"* until 2030 were estimated based on the "*APG Masterplan 2020*" (APG, 2011) and added to the total transmission grid investments in each of the four storylines.

Results on Grid Infrastructure Needs and Costs for RES-Electricity Integration in Austria in the Blue Storyline

Figure 18 presents the total cumulated transmission grid investments in Austria as a function of RES-Electricity deployment in the four different storylines.

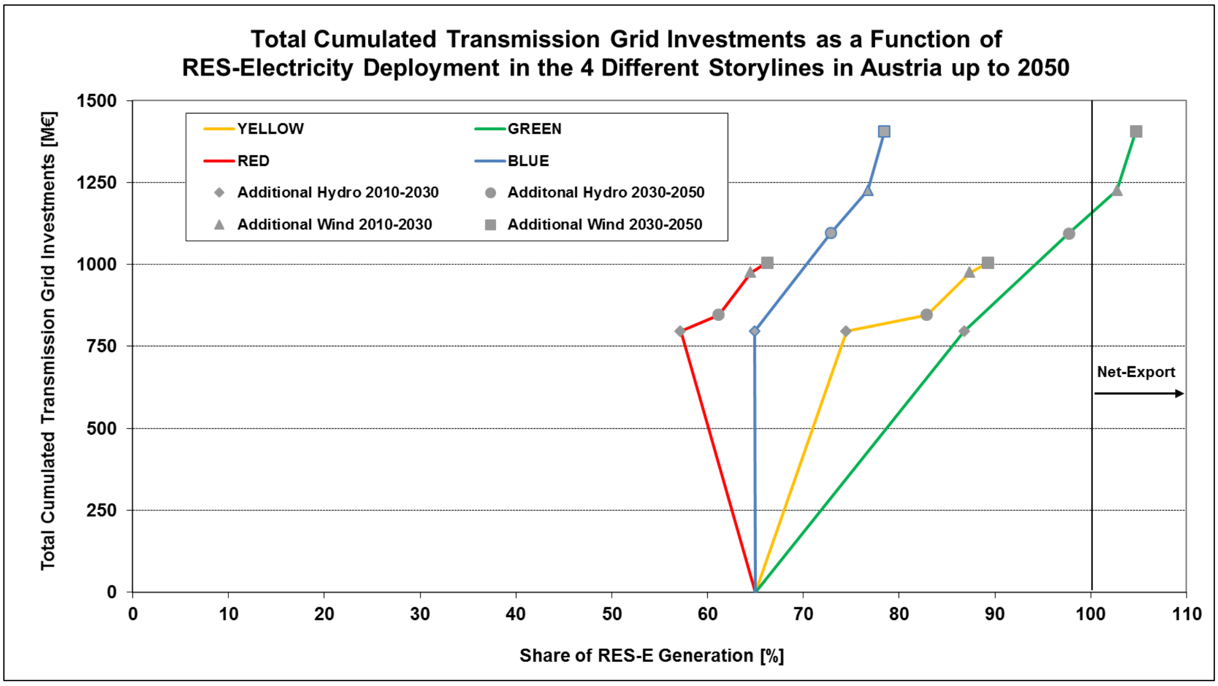

Figure 18: Total cumulated transmission grid investments as a function of RES-Electricity deployment in the four different storylines in Austria up to 2050 (Source: own calculations)

All storylines have the same starting point of a RES-Electricity share (on gross electricity consumption) of about 65% in 2010. In the *Red* storyline it can be observed that this share decreases continuously (high demand, low deployment of remaining RES-Electricity) and remains below the 2010 value until 2050, despite additional integration of wind and hydro generation from 2010–2050. Also in *Blue* the RES-Electricity share indicates a negative development at the beginning, but the high additional wind and hydro generation increases it to about 78% in 2050. Compared to *Red* and *Blue*, *Yellow* and especially *Green* show a continuously increasing RES-Electricity development. In the *Green* storyline more than 100% are reached in 2050, indicating that Austria becomes a net exporter of "green" electricity.

When studying the vertical axis of Figure 18, it can be seen that both storylines *Red* and *Yellow* show a similar growth in the total cumulated transmission grid investments and also reach a similar value in 2050. This indicates that both have about the same need for transmission grid expansion, but the reasons are different: in the *Red* storyline some of the transmission investment needs are also triggered by higher electricity demand increases and not exclusively by new RES-Electricity generation. The much higher RES-Electricity share of the *Yellow* storylines (compared to *Red*) however, is due to the higher share of PV generation, which does not trigger new transmission grid investments in our analysis. The same is true for *Blue* and *Green*, also here we see comparable transmission grid investment needs, but again in the *Blue* storyline these new transmission lines are not fully exploiting RES-Electricity generation. The higher transmission grid investments in *Green / Blue* compared to

Red / Yellow are triggered by higher amounts of integrated shares of wind and hydropower as well as the need to upgrade transmission routes to neighbouring countries to export electricity.

4.1.6 Discussion of the Austrian Results in the Electricity Sector

Closing the Austrian “*380 kV-Ring”* is clearly the most important issue in Austria in the short and medium term. Transmission adequacy within the footprint of Austria, furthermore, also enables further integration of the still not exploited hydropower and wind potentials.

Having in mind increasing shares of wind-onshore and wind-offshore installations in Central and Eastern European countries in the next decades, Austrian PHES potentials are an additional “*valuable asset*” in the medium to long-term; not least due to the fact that many of the Central and Eastern European countries are characterised by a rather inflexible power plant mix (e.g. Poland with its more than 90% coal-fired power plants; but also many other countries like Germany and Czech Republic with significant shares of nuclear and other base load power generation technology types).

Increasing shares of variable RES-Electricity generation, however, also result in increasing needs for flexibility of the electricity systems; but not necessarily inside the footprint of each country. And this is where Austria with its flexible power plant mix can contribute significantly to mitigate the variability problem of wind and PV generation in the Central and Eastern European countries. A precondition and necessity, however, is transmission grid expansion both inside the country and cross-border enabling access to flexible PHES.

4.2 Serbia

4.2.1 Status Quo of the Serbian Electricity Generation System

Thermal power plants covered approximately 75% of Serbian electricity generation in the year 2011. It is the main electricity generation technology in Serbia with an installed capacity of about 4 GW (cf. Table 4). Besides thermal generation, hydropower plants are the only electricity generation technology in Serbia with about 2.8 GW installed. Currently, there are two PHES systems in Serbia, Bajina Bašta and Lisina, with an installed capacity of 641 MW.

About 60% of the installed HPP capacities have an average age of 40 years; some of the plants are older than 50 years. Therefore, the rehabilitation of HPPs is one of the main priorities of Serbian energy sector. Additionally, there are about 60 small-scale HPPs in the country but only 27 of them, with an installed capacity of about 26 MW, are in operation. The others need revitalisation (Linnerud et al., 2010).

Table 4: Electricity generation system in Serbia in the year 2011 (Source: EPS, 2011b, EPS, 2009)

Electricity Generation System in Serbia 2011					
Power Plant Technologies		Count	Power Capacity [MW]	Electricity Generation [GWh]	Share on Total Electricity Generation
HPP	Run-of-River	6	1,852	7,876	21.85%
	(P)HES	9	983	1,269	3.52%
	Small-scale HPP (< 10 MW)[29]	~60	26	35	0.10%
	Sum HPP	**75**	**2,861**	**9,180**	**25.47%**
TPP	Lignite	6	3,936	26,462	73.40%
	Mixed fuels (natural gas / oil)	3	353	408	1.13%
	Sum TPP	**9**	**4,289**	**26,870**	**74.53%**
	(of which CHP-units)	(3)	(353)	(408)	(1.13%)
TOTAL		**84**	**7,150**	**36,050**	**100.00%**

Although there is considerable potential of "*new*" RES-Electricity (i.e. wind, PV, biomass, etc.) in Serbia, it is still unexploited to a large extent (only some small facilities exist for energy production for local community's needs) (EPS, 2011c). Also the introduction of feed-in-tariffs in the year 2010 (expired in 2012), did not trigger deployment of RES-Electricity until today due to long and complicated procedures. Subsequent tariffs are still unknown and, additionally, constant changes in legal regulations creating concernment with the potential investors (Kovandžić, 2011).

The domestic electricity consumption in Serbia in the year 2011 was 38,047 GWh, including 860 GWh for pumping purposes in Serbian PHES systems. In general, Serbia is a net importer of electricity. In the year 2011 the net import / export balance was about 2 TWh (imports).

So far, there has been no privatisation / deregulatory process in the electricity sector – there are two independent, state owned companies, Elektromreža Srbije (Serbian Transmission System and Market Operator – EMS) and Elektroprivreda Srbije (Electric Power Industry of Serbia – EPS).

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[29] Data source for small-scale HPP: Linnerud et al., 2010.

4.2.2 Short-term Development of the Serbian Electricity Generation System

According to the "*Strategic and Development Projects of the Electric Power Industry of Serbia*" (EPS, 2011a), the short-term development plan of EPS until 2025, the following projects are to be finalized within the forthcoming period: construction of four new TPP units with a total installed capacity of about 1.8 GW (i.e. Kolubara B, which construction stopped several years ago, Nikola Tesla B3, Kostolac B3), rehabilitation of several HPPs and TPPs (additional 385 MW of capacity) and construction and rehabilitation of small HPPs. Further on, the construction of some new 22 run-of-river HPPs on various rivers (in total about 800 MW) and PHES systems Djerdap 3 (1800 MW) and Bistrica (680 MW) is envisaged until the year 2025.

Other RES-Electricity generation technologies are not explicitly considered in the development plan. The engagements of the country and the regulatory framework, however, increase the interest in development of RES – mainly wind. Particularly high is the interest in wind energy in eastern part of Vojvodina. Currently wind energy projects with a total capacity of 1.4 GW are in different development states in Serbia (Serbia Energy, 2012).

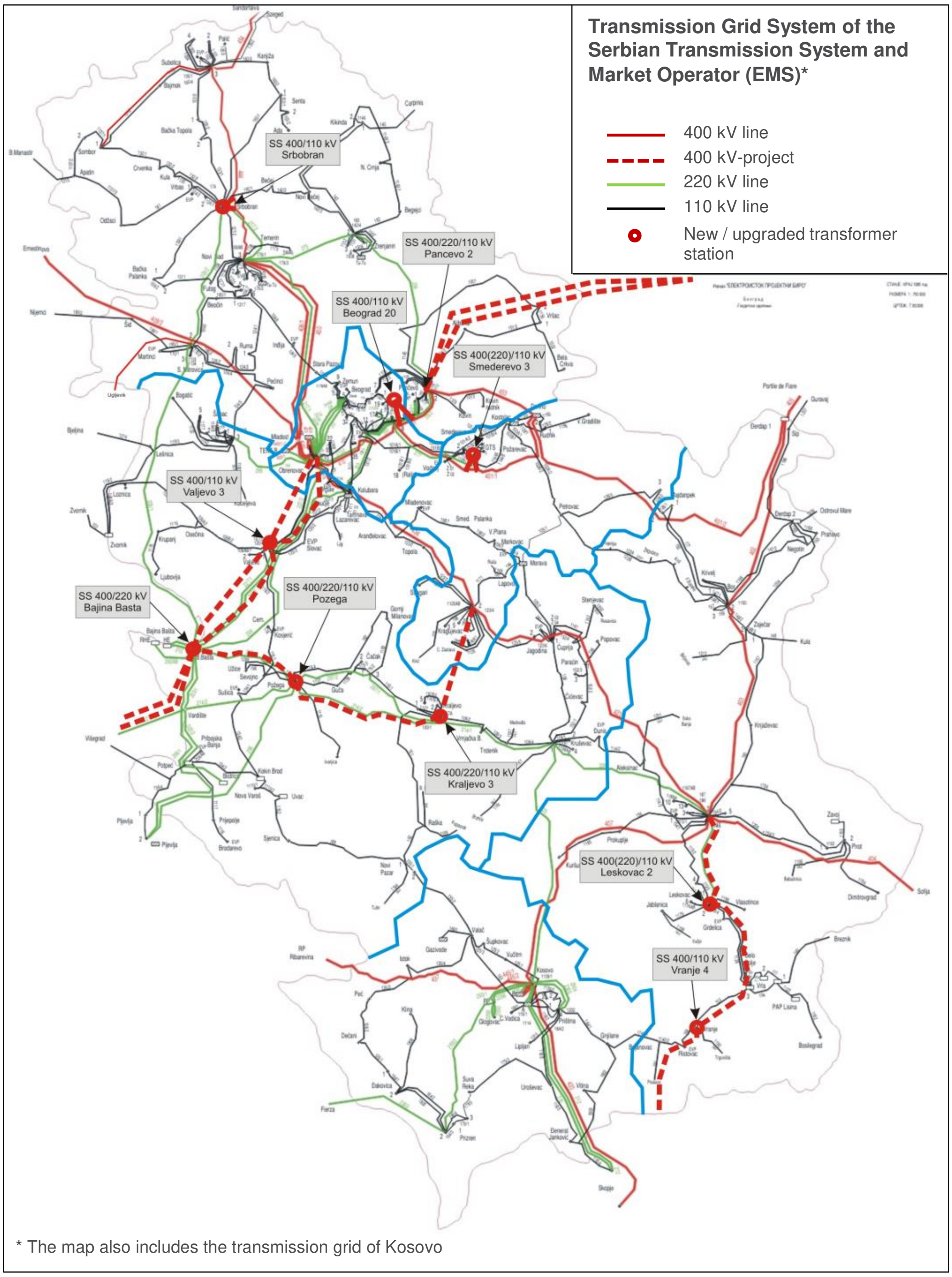
4.2.3 Status Quo of the Serbian Transmission Grid System

The status-quo and the expansion plan of the Serbian transmission grid system are shown in Figure 19. The Serbian transmission grid system is operated by EMS and consists of three different voltage levels: 400, 220 and 110 kV.

The partly obsolete and inefficient electricity transmission network in Serbia has to face some major updates in the future. The expansion plan, as identified in the "*Regional Investment Plan Continental South East*" (ENTSO-E, 2012b) of ENTSO-E's "*Ten Year Network Development Plan 2012*" (TYNDP2012) foresees reinforcements of the 400 kV transmission grid systems through construction of new lines and substations (SS) and gradual upgrade of the 220 kV system to 400 kV. Especially in the western part of the country, around the SS Bajina Basta–Obrenovac, transmission grid system enhancements are foreseen.

New interconnections / upgrades are foreseen with nearly all neighboring countries of Serbia:

- Romania (SS Pancevo–Resita), new 131 km double circuit 400 kV overhead line (OHL) to increase the transfer capability between the two countries and to accommodate new RES-Electricity generation (especially wind) on the western / eastern part of Romania and Serbia respectively;
- Montenegro (SS Bajina Basta–Pljevlja), new 86 km single circuit 400 kV OHL;
- Bosnia and Herzegovina (SS Bajina Basta–Visegrad), new 400 kV interconnection OHL and reconstruction of existing two 220 kV OHLs between the two countries to eliminate constraints in the region for electricity transits and exchanges;
- and FYR of Macedonia (SS Leskovac–Stip), new 220 km 400 kV single circuit OHL interconnection between the two countries.



* The map also includes the transmission grid of Kosovo

Figure 19: Long-term plan for the development of the Serbian 400 kV-grid of EMS (Source: EMS, 2012 & SEEC, 2009)

4.2.4 Analysis of the RES-Electricity Deployment in the Blue Storyline for Serbia

<u>Main Considerations for the Serbian Case Study in the Different Storylines</u>

For the future electricity demand development in Serbia two different paths are assumed:

- For *Yellow* and *Green* an annual electricity demand increase of 0.9% until 2030 and 0.7% until 2050 is used.
- In *Red* and *Blue* a higher annual electricity demand increase is used, 1.2% until 2030 and 1.4% until 2050.

Results on RES-Electricity Deployment in Serbia from 2010–2050 in the Blue Storyline

The result of the *GreenNet* modelling of the *Blue* storyline in Serbia from 2010 to 2050 is depicted in Figure 20[30]. It can be seen that electricity generation of newly installed HPP capacities (run-of-river and (P)HES, about +10 TWh/yr in 2050 compared to 2010) and wind (with about +3.8 TWh/yr in 2050) are the major contributors to the RES-Electricity increase in Serbia in the *Blue* storyline. The calculated wholesale electricity market price (from *EMPS*) in the *Blue* storyline is at a high level in 2030 with about 120 €/MWh, but then slightly decreases due to the higher shares of RES-Electricity generation in the European system in general to about 110 €/MWh in 2050.

The Serbian electricity generation portfolio in Figure 20 in the *Blue* storyline again shows that generation of newly installed RES-E capacities cannot cope with the high gross electricity demand increase. The electricity "*gap*" between the gross electricity demand and available RES-Electricity generation in Serbia in the *Blue* storyline increases steadily until 2050.

In *Blue*, a RES share (on gross electricity consumption) of about 46% can be achieved in Serbia in the year 2050.

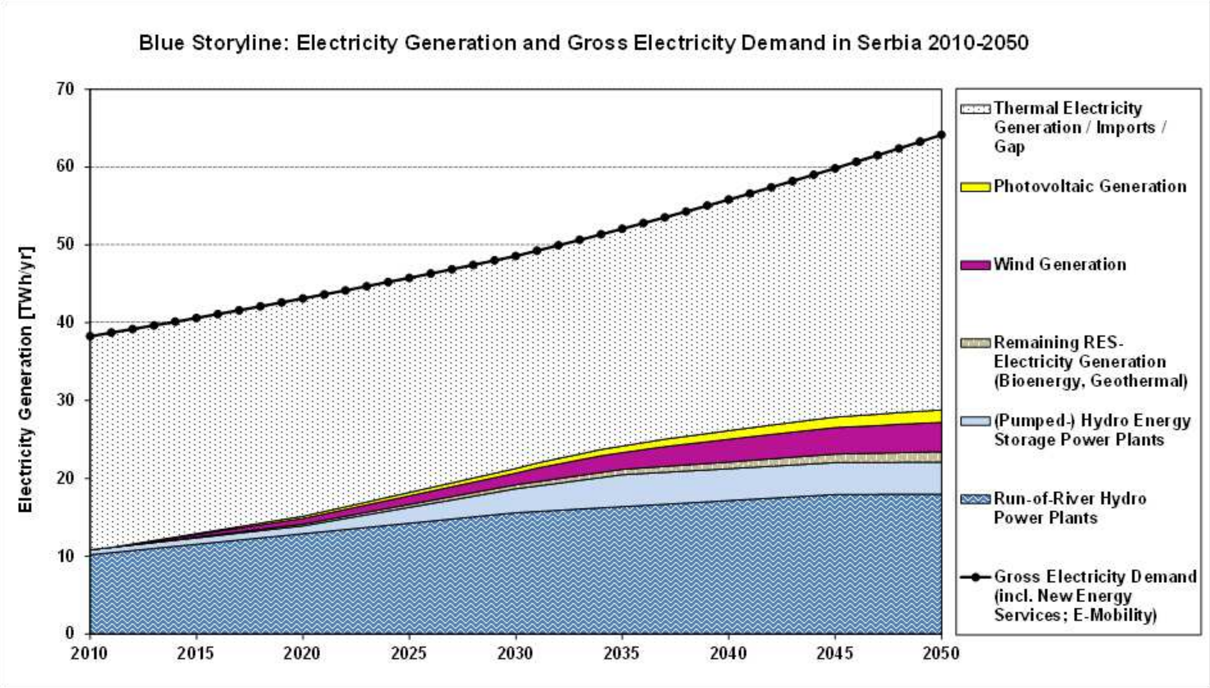


Figure 20: Electricity generation portfolio and gross electricity demand in Serbia from 2010 to 2050 in the *Blue* storyline (Source: own calculations)

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[30] See Appendix A.6 for the RES-Electricity deployment results of the remaining storylines for Serbia.

4.2.5 Analysis of the Electricity Grid Infrastructure Needs and Costs in Serbia

Main Considerations for the Serbian Case Study

The future development of the Serbian transmission grid system was already summarized in section 4.2.3. Figure 21 again shows the final stage of this development plan but additionally includes the major load centres of Serbia represented by black circles (the greater the circle the higher the respective load). Further on, also the geographic location of the main RES-Electricity potentials, small- / large-scale HPP and wind, are drawn in.

The future transmission grid routes (dotted red lines in Figure 21) of the development plan were taken as input to derive the results on transmission grid infrastructure needs and costs for further RES-Electricity integration in Serbia up to 2050.

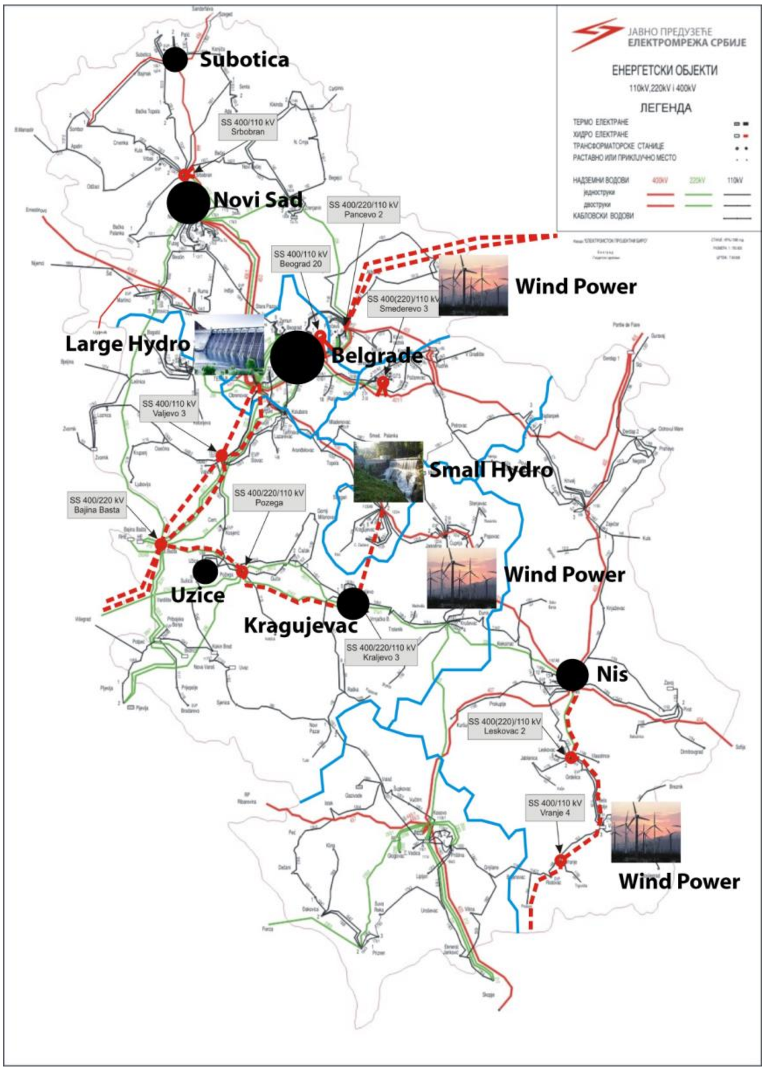

Figure 21: Spatial dispersion of RES-Electricity potentials, load centres and grid infrastructure routes in Serbia (Source: EMS, 2012 & SEEC, 2009)

The following results on transmission grid infrastructure needs and costs for further RES-Electricity integration in Serbia up to 2050 in the four different storylines are based again on an *eTransport* analyses (see section 3.1.1 for a comprehensive description of the *eTransport* model).

For this, missing transmission grid upgrades, extensions and routes needed to further integrate the remaining RES-Electricity potentials until 2050 were estimated based on the geographic location of the different RES-Electricity potentials. Since wind and hydropower are the only remaining major RES-Electricity potentials in Serbia that are connected on transmission grid level, the aggregated residual wind and hydropower potentials were located (cf. Figure 21) and set in relation to the possible future transmission grid routes. Then the lengths of the transmission grid lines which need to be upgraded / newly built to connect these RES-Electricity potentials to the main load centres / existing transmission grid were analysed.

The different aggregated RES-Electricity potentials and the main Serbian load centres were implemented in the *eTransport* model and linked to each other with lines of the respective lengths. The specific transmission grid costs for new HVAC OHL (single circuit) of 0.6 M€/km were taken from the project *"REALISEGRID"* (Rüberg et al., 2010) to be able to quantify the investment needs for the Serbian transmission grid caused by RES-Electricity integration until 2050.

Figure 22 shows a screenshot of the established *eTransport* analyses.

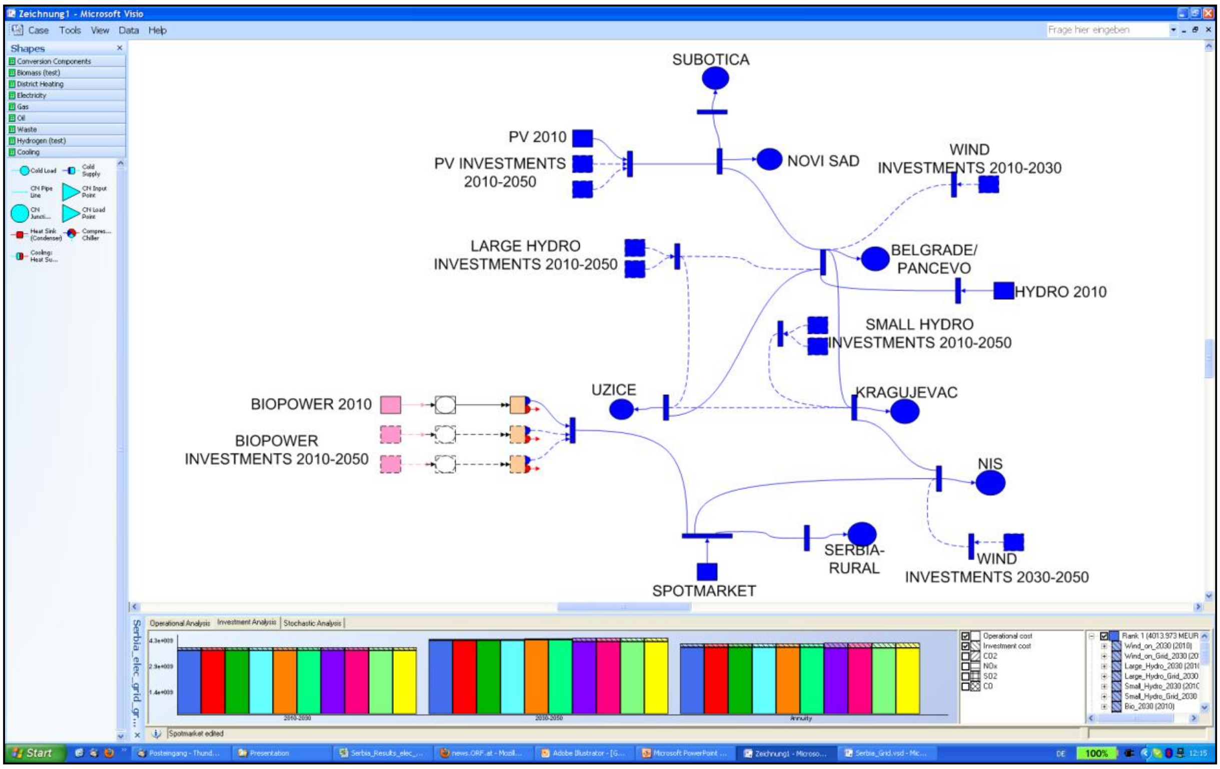

Figure 22: Screenshot of the established *eTransport* case for the analyses of the investment needs for the Serbian transmission grid until 2050

Results on Grid Infrastructure Needs and Costs for RES-Electricity Integration in Serbia in the Blue Storyline

Figure 23 presents the total cumulated transmission grid investments in Serbia as a function of RES-Electricity share (RES-Electricity generation on gross electricity demand) in the four different storylines.

All storylines have the same starting point of a RES-Electricity share of about 33% in 2010. In the *Red* storyline it can be observed that this share continuously decreases at first (high demand 2050, low deployment of remaining RES-Electricity technologies) and remains below the 2010 value despite additional integration of wind (2010–2030) and small hydro generation from 2010–2050. Also in *Blue* the RES-Electricity share indicates a negative development at the beginning, but the high additional wind and HPP generation increases it to about 46% in 2050. Compared to *Red* and *Blue*, *Yellow* and *Green* show a continuously increasing RES-E share development, especially because of the low demand increase and also the higher deployment of PV and bioenergy (both do not trigger new transmission grid investments in our analyses). In the *Green* storyline a RES-E share more than 60% is reached in 2050.

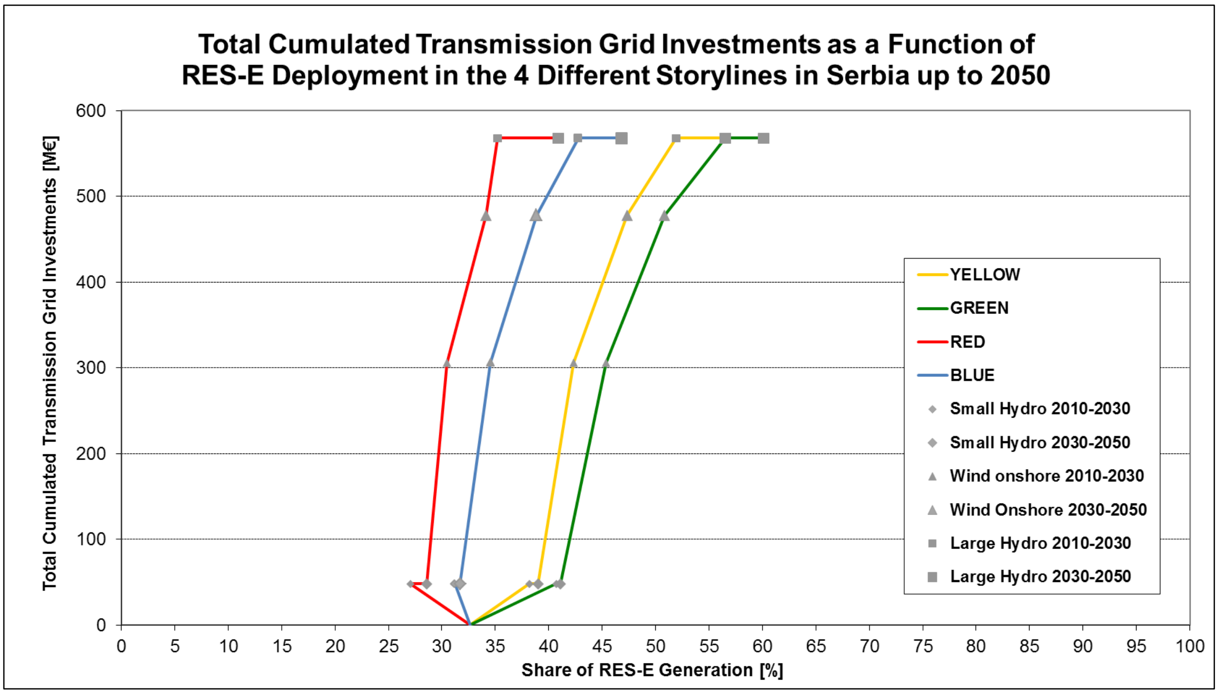

Figure 23: Total cumulated transmission grid investments as a function of RES-Electricity deployment in the four different storylines in Serbia up to 2050 (Source: own calculations)

When studying the vertical axis of Figure 23, it can be seen that all storylines show a similar growth in the total cumulated transmission grid investments and also reach a similar value in 2050. This indicates that all have a similar need for transmission grid expansion, but the reasons are different: in the *Red* storyline some of the transmission investment needs are also triggered by higher electricity demand increases and not exclusively by new RES-Electricity installations. Also in the *Blue* storyline these new lines are not fully exploiting RES-Electricity generation.

Wind integration expects the highest transmission grid investment needs in all four storylines. Hydropower does not trigger any further transmission grid investments after 2030.

4.2.6 Discussion of the Serbian Results in the Electricity Sector

Large amounts of Serbia’s currently unused RES-Electricity generation potential will be already integrated in the system until 2030. Therefore, besides the residual hydropower and wind potential, only low additional RES-Electricity generation potential is available in Serbia until 2050. Further RES-Electricity potentials like PV and other RES-Electricity technologies will only have a minor contribution.

Besides hydropower, thermal power will remain the main source for electricity generation in Serbia until 2050 in all storylines. Even in the *Green* storyline, where the above mentioned fast technological development and supporting schemes apply, thermal electricity generation (including import / export balance) stays more or less constant and cannot be decreased until 2050. The country will be continuously using its immense national lignite resources.

If the previously mentioned gas pipeline projects are being built thru or towards Serbia, thermal power generation from CCGTs is likely to be enhanced, the more so, as the further deployment of variable RES-Electricity technologies will require more flexible thermal generation.

The new RES-Electricity installations are not able to fully cover the yearly increasing gap between generation and demand, even if the annual electricity demand increase is rather low as in the *Green* and the *Yellow* storyline. Therefore, Serbia is not able to reach higher shares than 65% of RES-Electricity generation on the national gross electricity demand until 2050 in the four different storylines.

The Serbian power system has passed a difficult period of underinvestment and also destruction. Despite the serious improvements achieved during the last several years, some elements are still obsolete and need replacement and rehabilitation.

Therefore, upgrading of the existing transmission grid is clearly the most important issue in Serbia in the short and medium term. With the further expansion of the transmission grid as stated in the national long-term transmission grid development plan, transmission adequacy within the footprint of Serbia and also cross-border interconnections are established. This, furthermore, also enables further integration of the still not exploited hydropower and wind potentials.

4.3 Spain

4.3.1 Status Quo of the Spanish Electricity Generation System

Thermal power plants covered approximately 68% of Spanish electricity generation in the year 2011, whereas major parts were generated by nuclear and combined cycle gas turbines (CCGT). In total the installed capacity of TPP reached about 53,520 MW (see Table 5). In the year 2011, wind turbines with a summed installed capacity of about 21 GW were deployed in the Spanish electricity system, making wind the generation technology with the second largest power capacity. Further on, also solar technologies (i.e. PV and CSP) have continued to increase their generation capacity continuously, exceeding 5 GW of installed capacity in the year 2011.

In Spain, the main financial support scheme, the "*Régimen Especial*" – special regime, operated until the end of 2011 and was suspended at the beginning of 2012. Currently, no other support schemes for RES-Electricity are in place (RES LEGAL, 2012).

Table 5: Electricity generation system in Spain in the year 2011 (Source: REE, 2012b)

Electricity Generation System in Spain[31] 2011					
Power Plant Technologies			Power Capacity [MW]	Electricity Generation [GWh]	Share on Total Electricity Generation
HPP	RoR and HES		14,816	27,571	10.16%
	PHES		2,747		
	Special Regime HPP		2,041	5,283	1.95%
	Sum HPP		**19,604**	**32,854**	**12.11%**
TPP	Fossil Fuels	Coal	11,700	43,488	16.03%
		Fuel / Gas	1,492	0	0.00%
		Combined Cycle	25,269	50,734	18.70%
		Sum	38,461	94,222	34.73%
	Nuclear		7,777	57,731	21,28%
	Special Regime TPP		7,282	32,037	11,80%
	Sum TPP		**53,520**	**183,990**	**67.81%**
RES-E	Wind		21,091	41,799	15.40%
	Photovoltaics		4,047	7,081	2.61%
	CSP		1,049	1,823	0.67%
	Other RES-E		858	3,792	1.40%
	Sum RES-E		**27,045**	**54,495**	**20.08%**
TOTAL			**100,169**	**271,339**	**100.00%**

However, due to the simultaneous growth of wind farms and CCGT power plants during the last decade, the Spanish electricity system is suffering an overcapacity in installed power. Thus, the capacity factor of CCGT plants has been falling below 50% during the last years and other peak-load power plants were offline more or less the whole year 2011 (cf. fuel gas power plants in Table 5).

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[31] Data without Spanish extra-peninsular systems.

The domestic electricity consumption of Spain in the year 2011 was about 265 TWh, including 3.2 TWh for pumping purposes in Spanish PHES systems and 7.2 TWh own consumption of the power plants. In general, Spain is a net exporter of electricity to Portugal and Morocco. In the year 2011 the net import / export balance was about 6 TWh (exports). While historically Spain has been an importer of electricity from France, this exchange has been gradually reduced during the last years due to increased wind deployment. Nowadays, the net exchange is mainly balanced.

4.3.2 Short-term Development of the Spanish Electricity Generation System

Like Austria, also Spain still has a development potential for HPP and PHES. Additionally, solar and wind power, which are already strongly developed due to the good natural-space conditions, have high remaining potentials. Therefore, it is expected that solar and wind power will even increase their shares and significance in the Spanish electricity system in the future. Other RES-Electricity technologies (i.e. bioenergy, geothermal, small-scale HPP) are only of minor importance.

The deployment of RES-Electricity until 2020 according to the National Renewable Energy Action Plan of Spain (NREAP-ES, MITT-ES, 2010) is presented in Table 6. Further on, also the gross final electricity demand is given in Table 6 for the two different scenarios defined in NREAP-ES: a reference and an additional energy efficiency scenario. The resulting share of RES-Electricity generation on final consumption in the year 2020 is about 36% for the reference scenario and about 40% for the efficiency scenario respectively.

Table 6: Development of RES-Electricity according to the NREAP-ES (Source: MITT-ES, 2010)

Development of RES-E Technologies in Spain (NREAP)					
RES-E Technology		**2005**	**2010**	**2015**	**2020**
HPP	[MW]	18,220	18,687	20,049	22,362
	[GWh]	35,503	34,617	36,732	39,593
of which Pumping (PHES)	*[MW]*	*2,727*	*2,546*	*3,700*	*5,700*
	[GWh]	*5,153*	*3,640*	*6,577*	*8,023*
PV	[MW]	60	4,021	5,918	8,367
	[GWh]	41	6,417	9,872	14,316
CSP	[MW]	0	632	3,048	5,079
	[GWh]	0	1,144	7,913	15,353
Wind	[MW]	9,918	20,155	27,997	38,000
	[GWh]	20,729	40,978	57,086	78,254
Biomass	[MW]	601	752	965	1,587
	[GWh]	2653	4,517	5,962	10,017
Renewables in Electricity	**[MW]**	**26,072**	**41,701**	**54,277**	**69,844**
	[GWh]	**53,733**	**84,034**	**110,988**	**150,030**
Gross Final Electricity Consumption [GWh]	**Reference**	**291,680**	**291,401**	**344,795**	**416,540**
	Efficiency	**291,680**	**291,401**	**328,710**	**375,289**

4.3.3 Status Quo of the Spanish Transmission Grid System

Red Eléctrica de España (REE) is responsible for the operation of the Spanish transmission grid. In total, REE's transmission grid is composed of more than 40,200 kilometres of high voltage electricity lines. The main drivers for further upgrades of the Spanish transmission grid are (i) facilitating the evacuation of feed-in of new RES-Electricity installations and (ii) strengthening the internal transmission grid and the interconnections to other countries as well as of the peninsula with the Balearic Islands.

Due to the geographical position of Spain, the interconnection possibilities with the rest of Europe are very limited, currently only the interconnection with France allows an exchange of electricity with the rest of the European Union. However, the low interconnection capacity makes the Iberian Peninsula more or less an "*electrical island*".

Currently, Spain and France are connected by four HVAC lines (cf. Figure 24): there are two lines in the Basque Country (one 400 kV line Hernani–Argia and one 220 kV line Arkale–Argia), one line in Aragon (220 kV, Biescas–Pragnères) and one in Catalonia (400 kV, Vic–Baixas). In total, these four HVAC lines allow a maximum exchange capacity of around 1,400 MW. The future interconnection between Santa Llogaia and Baixas, a double-HVDC line (2 x 1,000 MW) which will be commissioned in 2014, will increase this exchange capacity to about 2,800 MW.

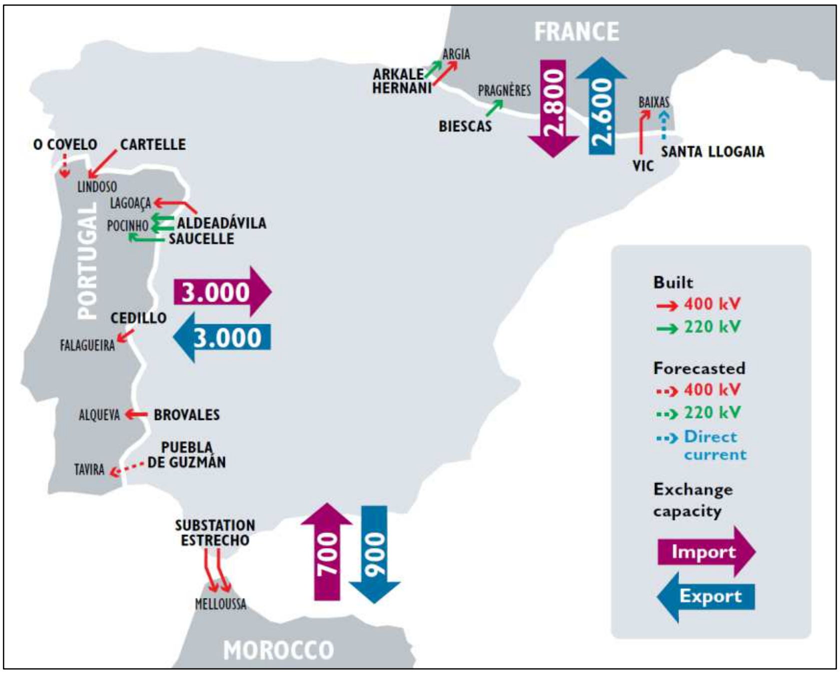

Figure 24: Existing and planned interconnection capacities of Spain (Source: REE, 2012a)

Besides the interconnection between Spain and France, also the cross-border transmission capacities between Spain and Portugal (from currently 2,400 to 3,000 MW) are being upgraded until 2016. Spain and Morocco are interconnected via two submarine power cables that provide a maximum capacity of about 800 MW.

4.3.4 Analysis of the RES-Electricity Deployment in the Blue Storyline for Spain

Main Considerations for the Spanish Case Study in the Different Storylines

As previously mentioned, the analysis of the Spanish electricity system was not performed by the author himself, but, in order to draw overall results and to make comparisons between different electricity systems, the modelling results of the Spanish system are also included in this paper. The modelling result data were taken from Frías et al., 2010.

The following demand growth rates were considered in Spain:

- For the *Green* and *Yellow* storylines 1% (2010–2020) and 1.5% (2020–2050) and
- for the *Red* and *Blue* storylines the same demand growth rate is considered for the whole period (2010–2050): 2% per year.

Results on RES-Electricity Deployment in Spain from 2010–2050 in the Blue Storyline

Figure 25 shows the results on RES-Electricity deployment in the *Blue* storyline in Spain from 2010–2050. In the Blue storyline, RES-Electricity share on gross electricity consumption rises from about 30% to about 63% in the period of 2010–2050. The highest contribution to this increase has wind energy (more than 190 TWh in the year 2050) and solar energy (more than 100 TWh in 2050). Also PHES generation increases from 2 TWh in 2020 to 5 TWh in 2050 due to high integration of variable RES-Electricity in the system in 2050.

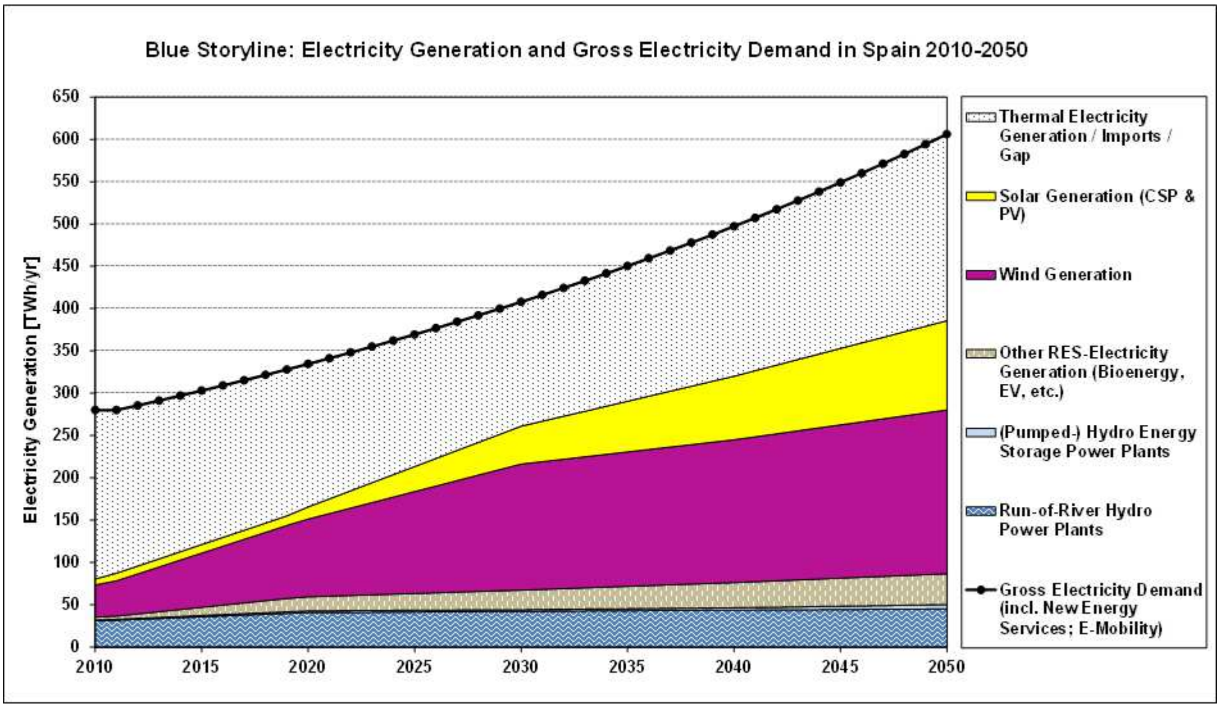

Figure 25: RES-Electricity generation portfolio and gross electricity demand in Spain from 2010 to 2050 in the *Blue* storyline (data source: Frías et al., 2010, own depiction)

4.3.5 Analysis of the Electricity Grid Infrastructure Needs and Costs in Spain

Figure 26 presents the impact of RES-Electricity deployment on the transmission grid investments in Spain in the *Blue* storyline. It can be seen that higher RES-Electricity penetration leads to higher required investments in the transmission grid. In *Green* the total required investments in transmission grid infrastructures are highest with more than 13 billion € in 2050. In the *Blue* storyline, requirements are over 10 billion € (including additional interconnection costs of 1.5 billion € for the DESERTEC project / North Africa). The main reason for higher investment costs in *Green* than in *Blue* is the higher interconnection needs in the former storyline. Due to the lowest interconnection requirements and also the lowest penetration of offshore wind, the *Red* and *Yellow* storylines have the lowest transmission grid investment costs in 2050 – approximately 6 billion € each.

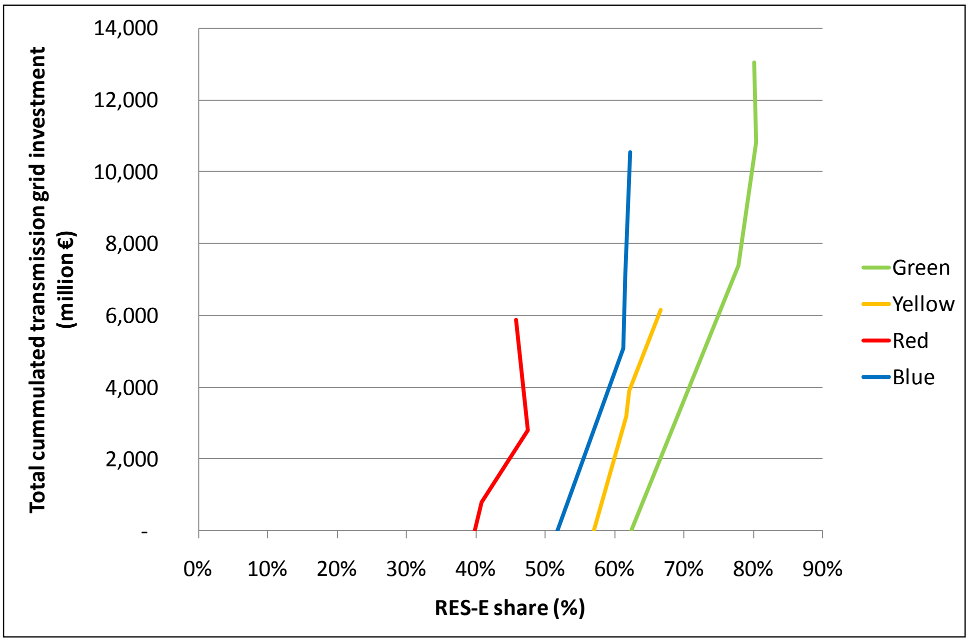

Figure 26: Total cumulated transmission grid investment cost over RES-Electricity penetration in the four different storylines up to 2050 in Spain (Source: Frías et al., 2010)

4.3.6 Discussion of the Spanish Results in the Electricity Sector

Despite the beneficial effects of RES penetration on carbon emissions and fuel costs, the realizations of scenarios with a high share of (variable) RES-Electricity generation – with up to 80% of the total electricity production by 2050 – also creates important challenges especially in the operation of the weakly interconnected Spanish power system. The main challenges are higher levels of RES-Electricity generation surpluses and higher operational reserves needs. These challenges can be met with the integration of backup conventional generation, electricity storage options (PHES, electric vehicles, etc.), new interconnection capacity (e.g. to France) and / or other flexible resources.

The biggest additional drivers for transmission investment in Spain in future scenarios will be the connection of offshore wind farms and the need to increase transmission interconnection capacity.

4.4 Analysis of the European Electricity Market Regions

4.4.1 Setup and Input Data

Establishment of hourly RES-Electricity generation data sets for the Electricity Market Regions in the years 2030 and 2050

For the derivation of the load duration curves and residual load curves in the different European Electricity Market Regions (EEMR; see also section 3.1.3) 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 2011 (ENTSO-E, 2012a). For the analyses of the electricity market regions, the same growth rates of electricity demand were applied as in the respective case studies in the *Blue* storyline for the different time periods. 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 2030 and 2050.
- ***Hourly CSP, PV and Wind Electricity Generation:*** To establish an hourly CSP, PV and wind electricity generation dataset for each electricity market region, real hourly CSP, PV and wind generation data was used from selected countries from the year 2011 and up-scaled accordingly: the Spanish data set from the Spanish TSO *Red Electrica* for the Iberian Peninsula (REE, 2012c) and the German[32] and Austrian[33] data sets for the CWE and Western Balkan region.
- ***Hourly Electricity Generation of Other Renewables:*** Other RES-Electricity technologies (e.g. biomass, biogas, geothermal, etc.) were approximated as constant generation bands throughout the year.
- ***Hourly Run-of-River Hydro Electricity Generation:*** The hourly run-of-river (RoR) hydro electricity generation for the Iberian Peninsula was established again by up-scaling of the real RoR hydro generation data set of the Spanish TSO *Red Electrica* of the year 2011 (REE, 2012c). Since no real data sets were available for Germany or Austria, average daily water-level values of the Rhine and Danube river[34] were taken to establish hourly RoR electricity generation data (linearly scaled between the measurement points and multiplied by the respective installed HPP capacities in the region) for the CWE and Western Balkan region.

An example for the established sets of regional residual load curves is shown in Figure 27, where the load duration and residual load curve for the CWE region in the *Blue* storyline in the year 2030 is given. In general, the residual load is calculated as follows (Equation 6):

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[32] Data was used from the German TSOs *50hertz* (50Hertz, 2012), *Amprion* (Amprion, 2012), *TenneT* (TenneT, 2012) and *TransnetBW* (TransnetBW, 2012).

[33] Data was used from the Austrian TSO *APG* (APG, 2012).

[34] Data was used from *eHYD* (Lebensministerium.at, 2012), monitoring points *Lustenau* (No. 200196, Rhine) and *Wehrstelle KW Aschach* (No. 207035, Danube).

Equation 6: $\boldsymbol{RL(t) = ED(t) - RE_{PV}(t) - RE_{CSP}(t) - RE_{Wind}(t) - RE_{Other} - RE_{RoR}(t)}$

$RL(t)$ … Residual load in hour t
$ED(t)$ … Electricity demand in hour t
$RE_{PV}(t)$ … RES-Electricity from PV installations in hour t
$RE_{CSP}(t)$ … RES-Electricity from CSP installations in hour t
$RE_{Wind}(t)$ … RES-Electricity from wind installations in hour t
RE_{Other} … Electricity from other RES-Electricity technologies
$RE_{RoR}(t)$ … RES-Electricity from RoR HPP in hour t

The residual load curves (green line in Figure 27) were generated by subtracting hourly PV (yellow area), wind (purple area), other RES-Electricity (green area) and run-of-river hydro (blue area) electricity generation from the load duration curve (black line). Note, that after every subtraction of respective RES-Electricity 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-Electricity feed-in at a certain point in time simply because it represents RES-Electricity feed-in data from different points in time. The surface area of the different coloured parts results in the total electricity generated in the year by the respective RES-Electricity technology.

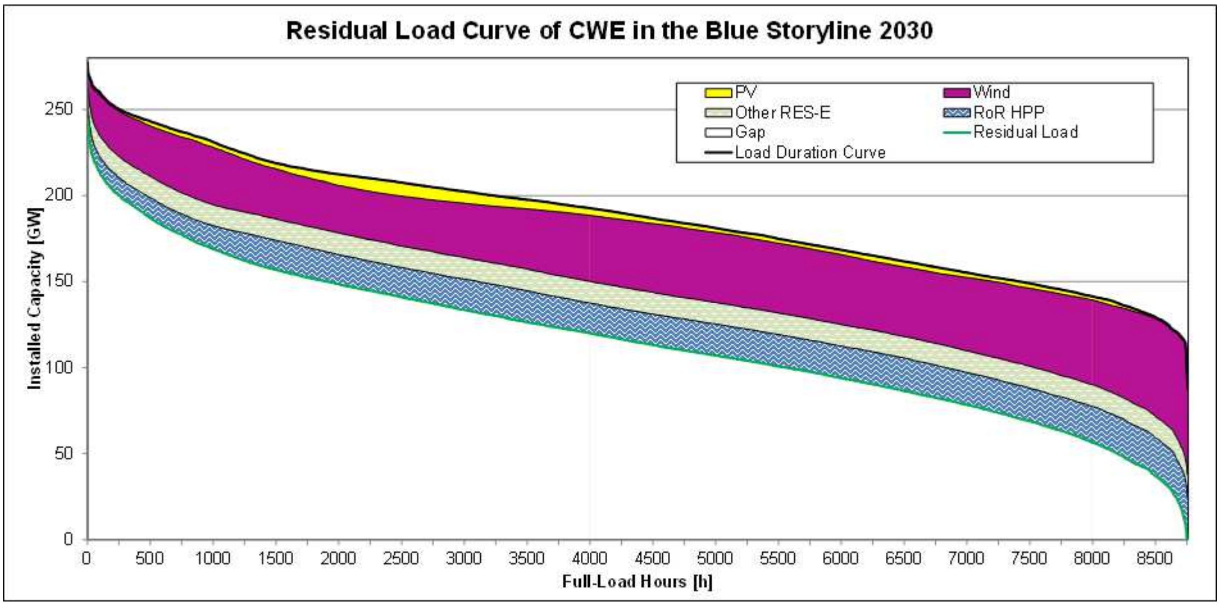

Figure 27: Load duration and residual load curve for the CWE region in the *Blue* storyline in 2030 (Source: own calculations)

Consideration of the age structure of the existing thermal power plant portfolio for the years 2030 and 2050

The currently existing thermal power plant-portfolio (e.g. nuclear, lignite, coal, etc.) within each of the different European electricity market regions was also considered in the analysis. 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.

Figure 28 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 the other two analysed European electricity market regions are given in the Appendix A.1.

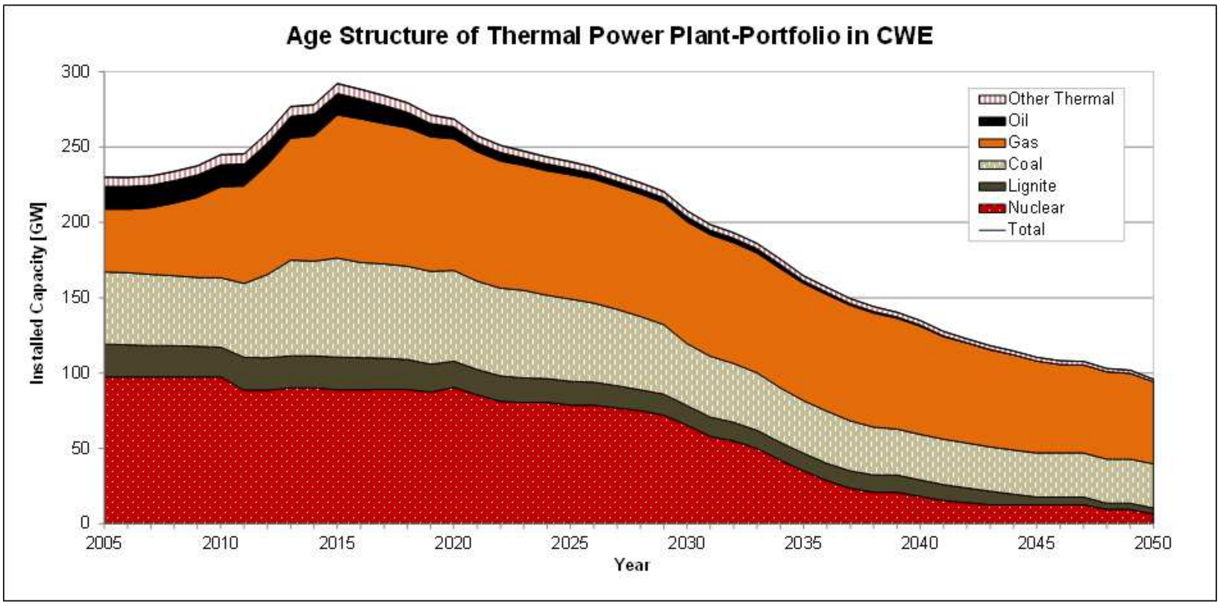

Figure 28: Age structure of the thermal power plant-portfolio in the CWE region (Data source: PLATTS, 2010)

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

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 29). 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 also incorporate power plant availabilities (i.e. offline periods due to maintenance etc.), installed thermal power plant capacities were multiplied by a factor of 0.8 (nuclear)[35] and 0.85 (all other thermal power plants)[36] respectively.

Additionally, currently existing, licensed and planned 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. (cf. Figure 29). The electricity consumption of existing and future PHES systems in pumping mode is not incorporated in the residual load curves in this stage of the analysis. However, in

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[35] Cf. EEA, 2012.

[36] Cf. EURELECTRIC, 2011b.

general this additional demand would only alter the residual load values in times of high RES-Electricity 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.

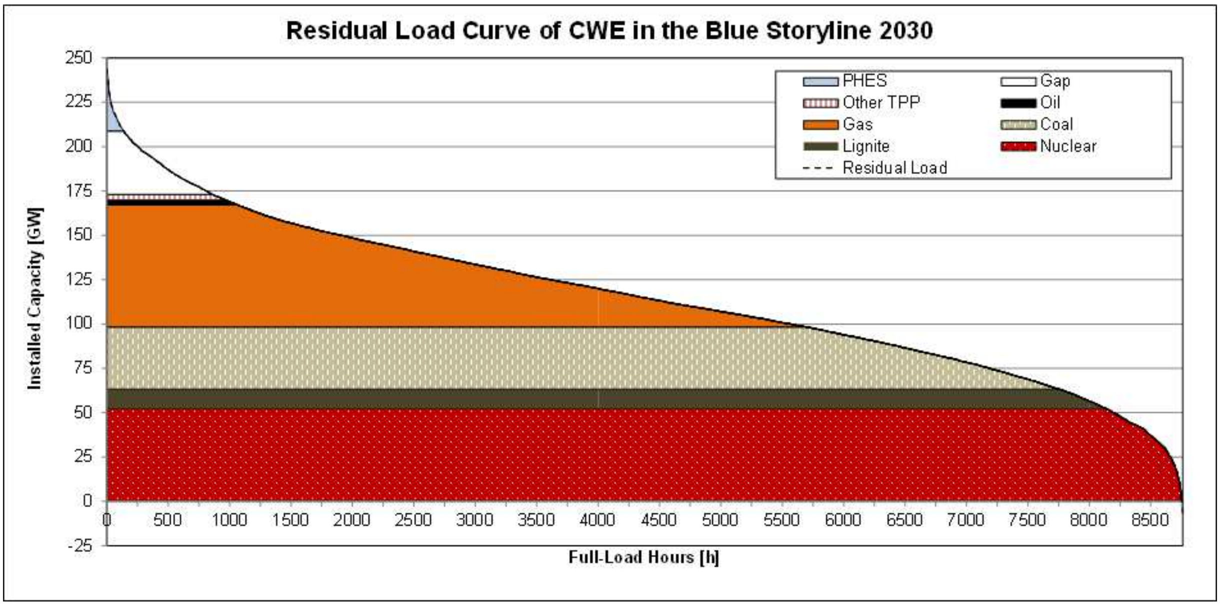

Figure 29: Coverage of the 2030 residual load of the CWE region with existing thermal power plants and PHES in the *Blue* storyline (Source: own calculations)

Figure 29 shows the coverage for the 2030 residual load in the CWE region with existing thermal power plants and PHES systems in the *Blue* storyline. It can be seen that in the CWE region a capacity gap of about 35 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[37]. The major still existing and available TPP in 2030 in the CWE region are gas-fired TPP (about 68 GW) followed by nuclear (about 52 GW) and coal-fired TPP (about 35 GW).

Integration of Surplus RES-Electricity Generation with PHES systems

In the final step of the analysis, the established PHES optimization algorithm is executed (cf. methodology in section 3.1.3). Based on the conducted literature review, the maximum available turbine / pumping power of the PHES system in the CWE region in the year 2030 was set to 35 / 30 GW and the maximum storage capacity was defined to 4,000 GWh.

The result of the PHES optimization for the CWE region in the year 2030 is shown in Figure 30. The light blue area indicates the difference between the original residual load curve (black dashed line in Figure 30) and the updated residual load curve also incorporating the PHES operation (blue line in Figure 30). It can be seen that the PHES system provided peak-load power (i.e. reduction of original residual load curve due to turbine operation on the left side of

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[37] Certainly, also higher RES-Electricity deployment (as e.g. in the *Green* storyline) would lower this capacity gap.

Figure 30 until about 4000 full-load hours) and created additional electricity demand due to pumping in off-peak times (i.e. increase of the original residual load curve from about 4000 full-load hours on in Figure 30). By doing so, the full-load hours of base-load TPP (i.e. nuclear, coal and lignite) are also increased and therefore these technologies get more economical. Further on, the small amount of excess RES-Electricity in the CWE region in the year 2030 is integrated in the electricity system due to storage operation of the PHES system. The storage capacity use of CWE's PHES system in the year 2030 is shown in Figure 31. It can be seen that the energy storage (i.e. upper reservoir of PHES system) is fully charged and fully emptied several times per year by the optimization algorithm without seasonal differences. Due to the optimization constraint (i.e. same end- and start-value) the stored energy reaches 2,000 GWh at the end of the year.

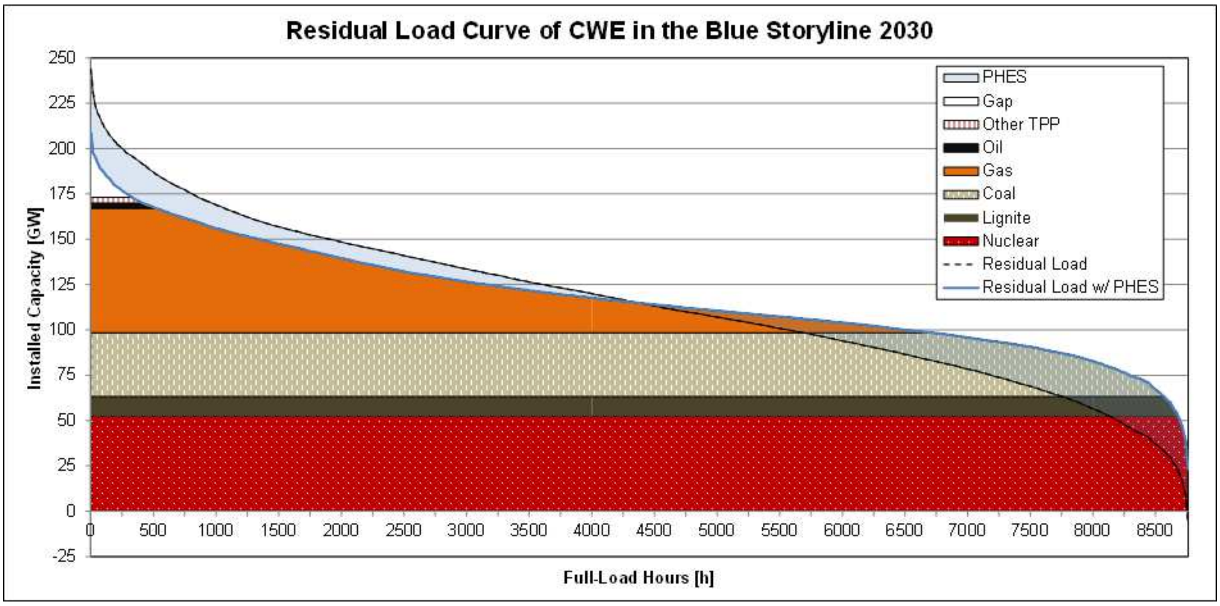

Figure 30: Coverage of the 2030 residual load after PHES optimization in the CWE region with existing thermal power plants in the *Blue* storyline (Source: own calculations)

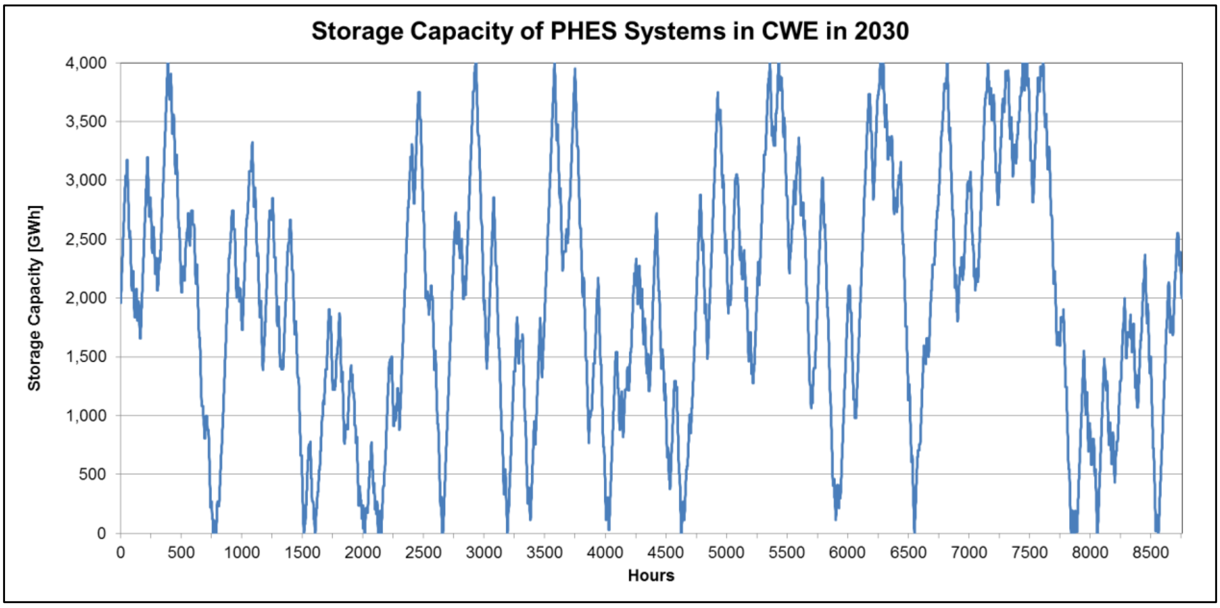

Figure 31: Storage capacity of the PHES system in the CWE region in the year 2030 (Source: own calculations)

4.4.2 Central Western Europe

In the *Blue* storyline RES-Electricity feed-in exceeds electricity demand for some time in the year 2050[38] in the CWE region (cf. Figure 32 and dashed line in Figure 33). This RES-Electricity 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.

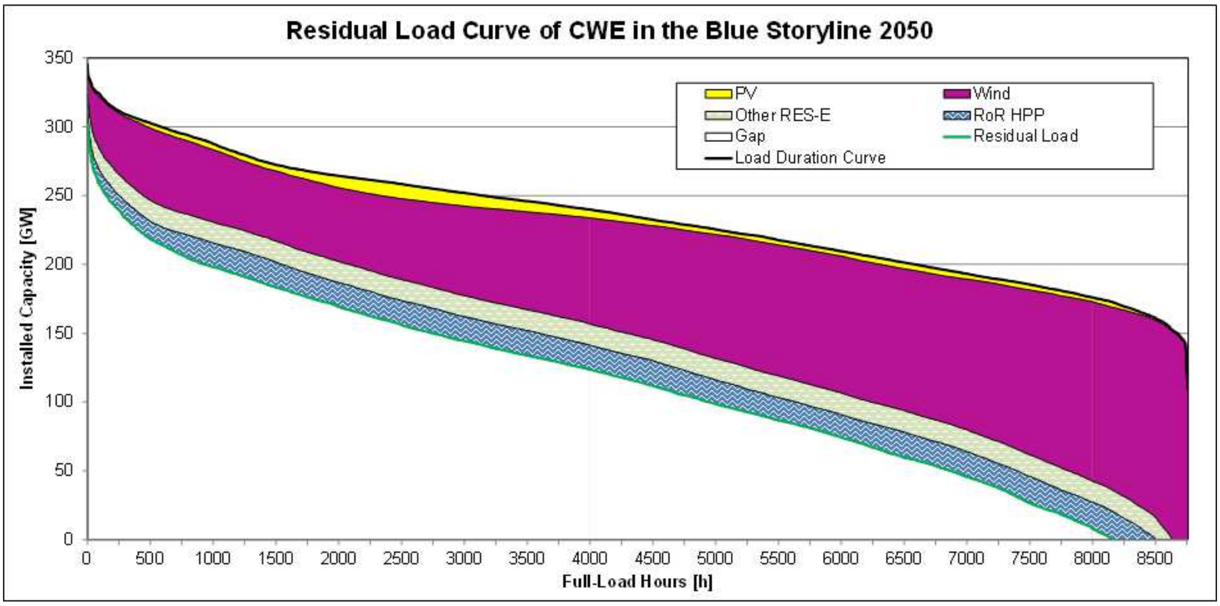

Figure 32: Load duration and residual load curve for the CWE region in the *Blue* storyline in 2050 (Source: own calculations)

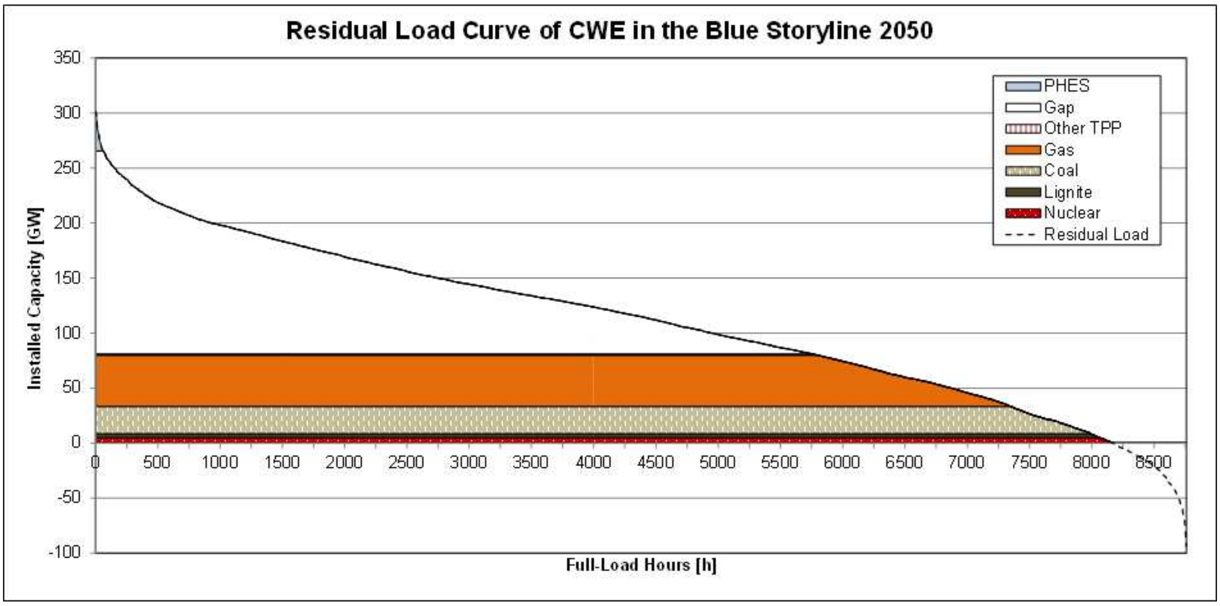

Figure 33: Coverage of the 2050 residual load of the CWE region with existing thermal power plants and PHES in the *Blue* storyline (Source: own calculations)

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[38] Results for the *Blue* storyline in the year 2030 were already presented in section 4.4.1.

However, due to phase-out of the majority of nuclear and lignite power plants in the region and high electricity demand increase, large amounts of integrated RES-Electricity cannot hamper the growth of the gap of missing generation capacity in comparison to the 2030 scenario (cf. Figure 29 and Figure 33). Especially the generation of newly installed wind power plants (on- as well as off-shore) contribute to lowering the residual load substantially. Only some generation capacities of gas- and coal-fired TPP are still available in the CWE region in 2050. Therefore, the "generation gap" amounts to about 190 GW in 2050.

Coverage of the 2050 residual load after PHES optimization in the CWE region with existing thermal power plants can be seen in Figure 34. For the optimization in the year 2050 the same parameters of the PHES system were used as in 2030. Again the typical PHES system operation scheme – provision of peak-load power and consumption of off-peak power – can be observed in the CWE region in 2050. Additionally, about 80% of the annual surplus RES-Electricity generation can be integrated (i.e. stored) in the inherent electricity system. The high negative peak of the residual load precludes that all surplus RES-Electricity generation can be integrated in the system – the PHES system is not sufficient and more pumping power is needed for full RES-Electricity integration.

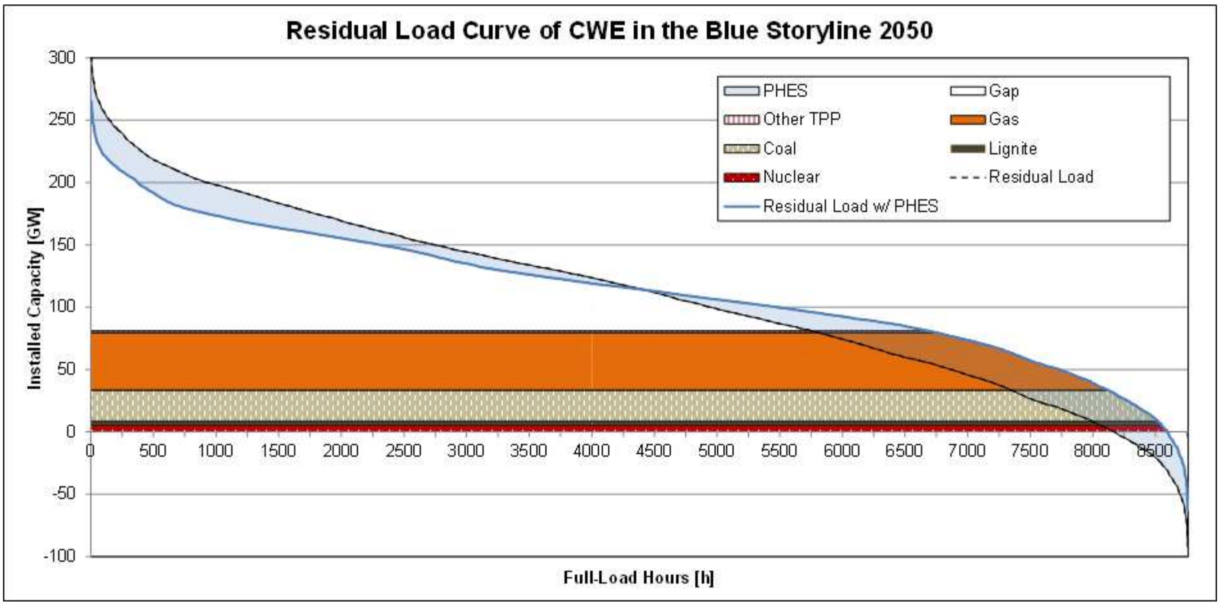

Figure 34: Coverage of the 2050 residual load after PHES optimization in the CWE region with existing thermal power plants in the *Blue* storyline (Source: own calculations)

4.4.3 Western Balkan

Figure 35 presents the load duration and residual load curve for the Western Balkan region in the *Blue* storyline in the year 2030. It can be seen that the major RES-Electricity source in the region are RoR HPP and wind power plants. Already in the year 2030 the RES-Electricity generation exceeds the demand occasionally due to high generation of RoR HPP. Again, this surplus RES-Electricity generation can either be used for export or for storage purposes.

The coverage of the residual load curve of the Western Balkan region in 2030 can be seen in Figure 36. Due to high (P)HES and still existing and available TPP capacities (especially lignite- and gas-fired) the gap only amounts to about 1.5 GW in the Western Balkan region.

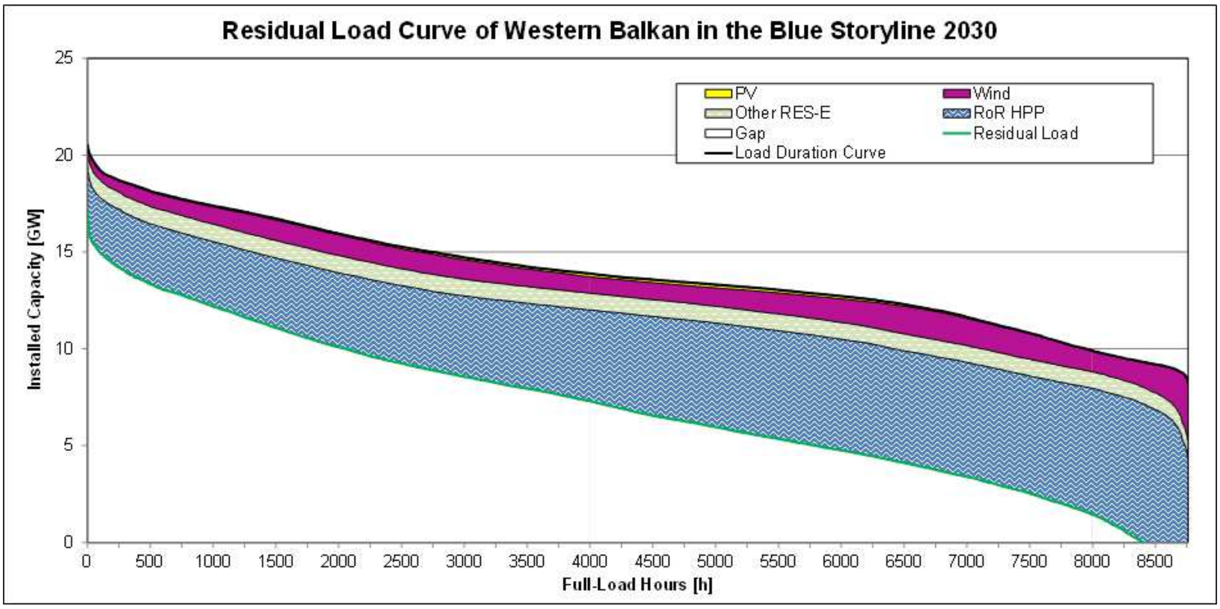

Figure 35: Load duration and residual load curve for the Western Balkan region in the *Blue* storyline in the year 2030 (Source: own calculations)

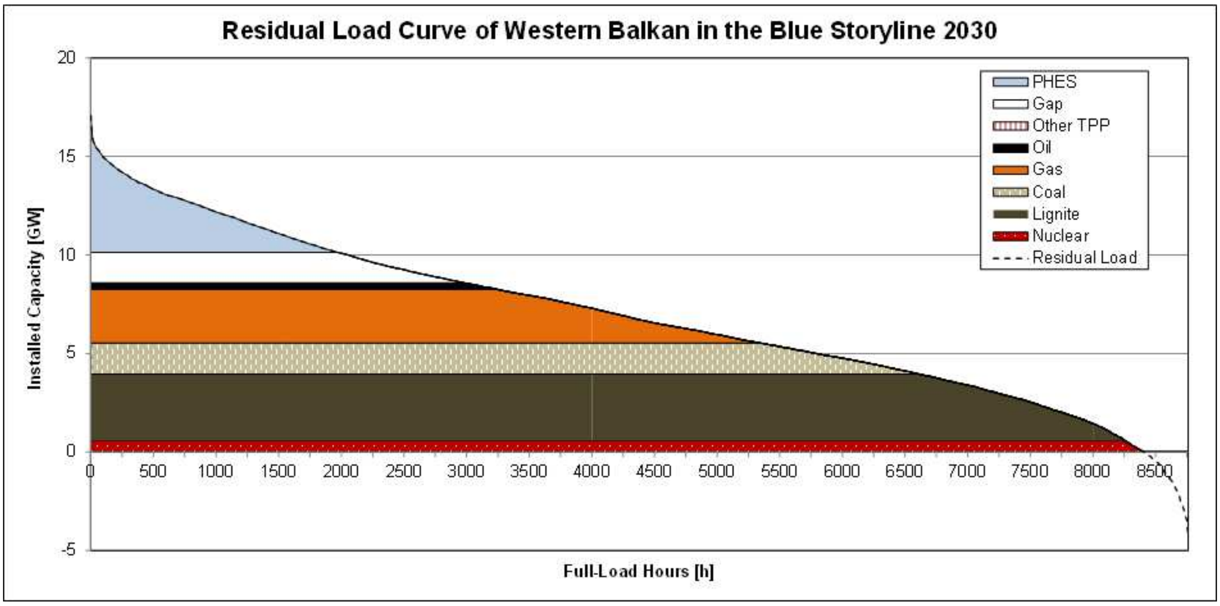

Figure 36: Coverage of the 2030 residual load of the Western Balkan region with existing thermal power plants and PHES in the *Blue* storyline (Source: own calculations)

Based on the conducted literature review, the maximum available turbine / pumping power of the PHES system in the Western Balkan region in the year 2030 was set to 7 / 5 GW and the maximum storage capacity was defined to 1,000 GWh.

The result of the PHES optimization for the Western Balkan region in the year 2030 is shown in Figure 37. It can be seen that the PHES system is capable to reduce the residual peak-load to about 12 GW and to integrate all excess RES-Electricity in the system. For about 460 hours of the year the electricity consumption of the Western Balkan region can be met by RES-Electricity technologies and PHES systems only (indicated by a residual load of 0 GW).

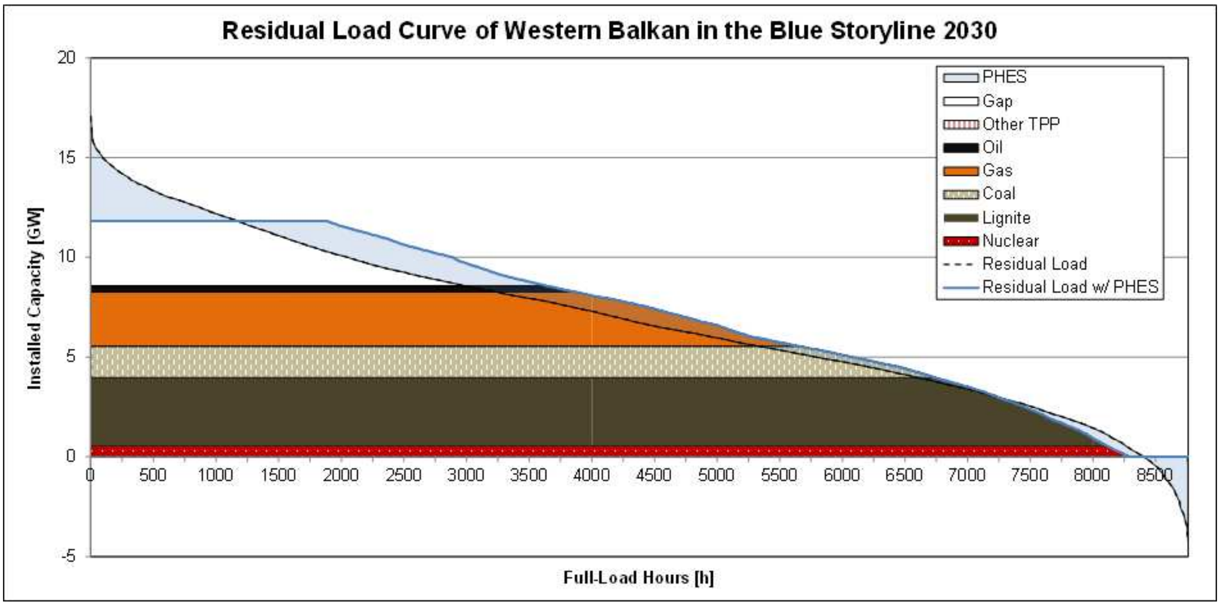

Figure 37: Coverage of the 2030 residual load after PHES optimization in the Western Balkan region with existing thermal power plants in the *Blue* storyline (Source: own calculations)

In comparison to the 2030 residual load curve (Figure 35), the residual load curve of the Western Balkan region in 2050 (Figure 38) does not change very much – only a small increase in wind and PV generation as well as an increase in the electricity load can be observed.

The coverage of the residual load curve of the Western Balkan region in 2050 (Figure 39) shows that about 1/3 of the available TPP and all nuclear capacities – ceteris paribus – in the region phase-out between 2030 and 2050. Hence, the gap of missing capacity increases to about 9 GW in 2050. However, due to the electricity consumption increase in the region the excess RES-Electricity generation can be reduced to about 240 GWh in the year 2050.

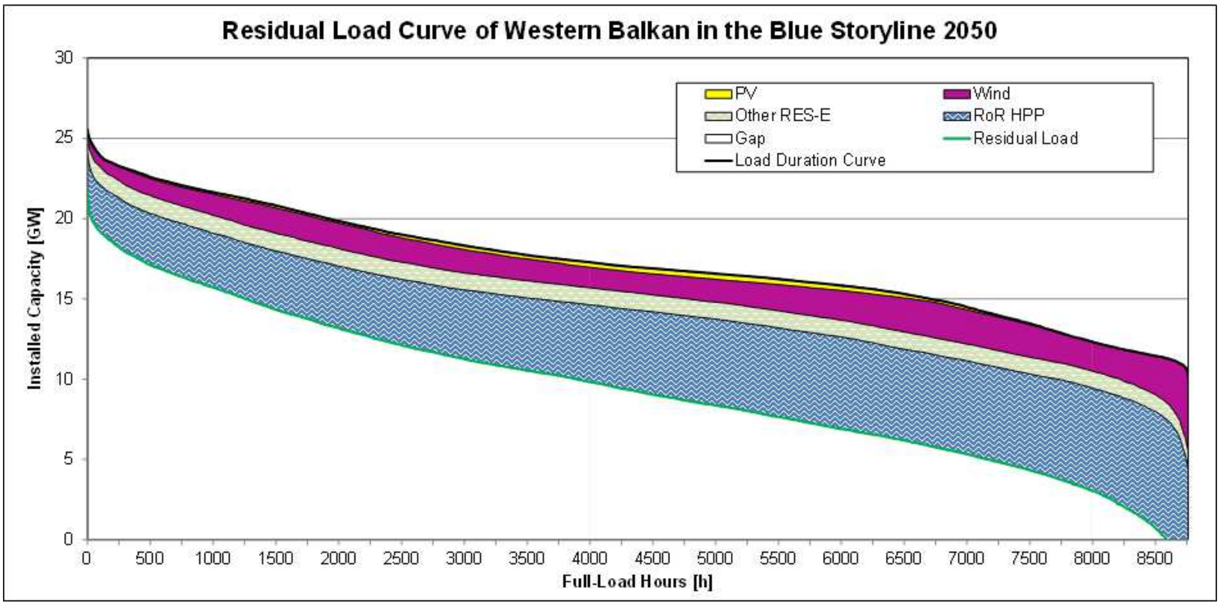

Figure 38: Load duration and residual load curve for the Western Balkan region in the *Blue* storyline in the year 2050 (Source: own calculations)

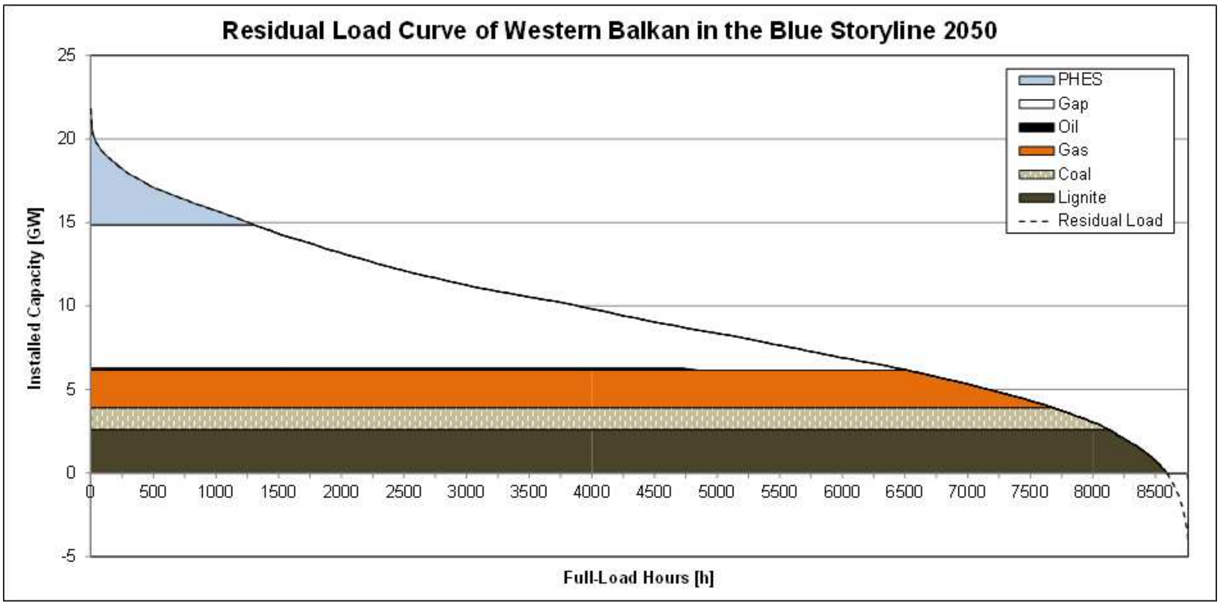

Figure 39: Coverage of the 2050 residual load of the Western Balkan region with existing thermal power plants and PHES in the *Blue* storyline (Source: own calculations)

For the PHES optimization in the year 2050 the same parameters were used as in 2030. The results of the PHES optimization in the Western Balkan region in the year 2050 are depicted in Figure 40. Again the annual peak-load of the region can be reduced and excess RES-Electricity can be fully stored by the PHES system – the PHES system seems to be sufficient for the region's needs. During the remaining time of the year, i.e. in off-peak times without surplus RES-Electricity, the residual load curve is hardly altered by the PHES system operation. Unlike in 2030, the residual load is not reduced to zero by the PHES system in the year 2050. Therefore, TPP are needed to satisfy the electricity consumption throughout the year 2050.

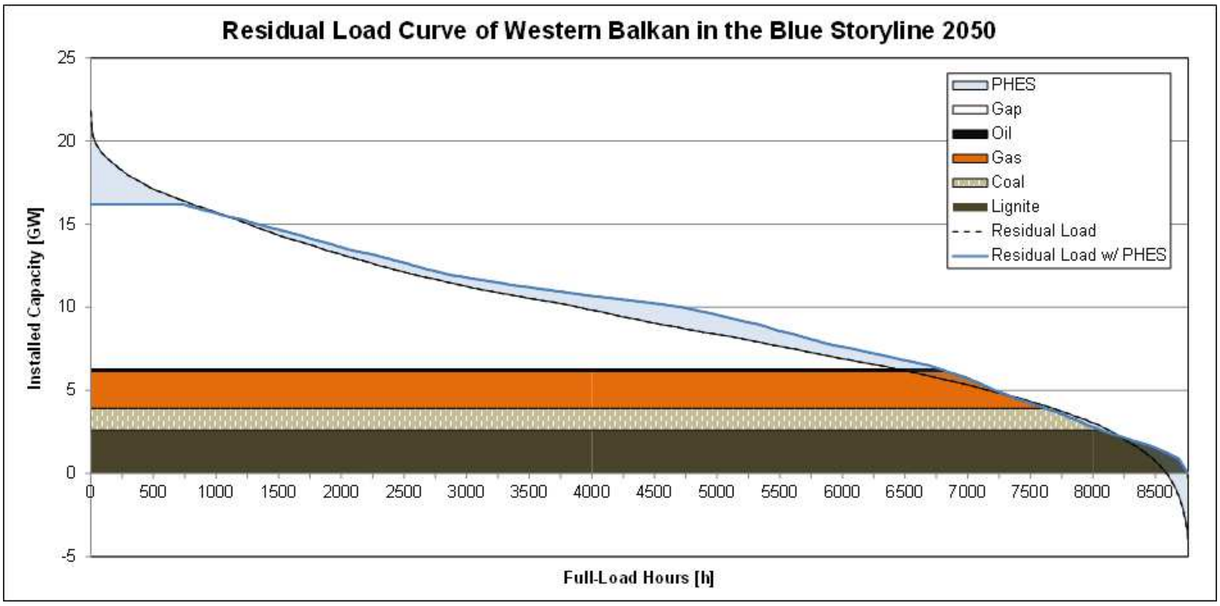

Figure 40: Coverage of the 2050 residual load after PHES optimization in the Western Balkan region with existing thermal power plants in the *Blue* storyline (Source: own calculations)

4.4.4 Iberian Peninsula

Figure 41 and Figure 42 show the construction of the residual load curve and its coverage with existing thermal power plants and PHES in the *Blue* storyline for the Iberian Peninsula in the year 2030. Already in 2030 RES-Electricity feed-in exceeds electricity demand for quite some time (about 2,000 hours) of the year 2030 in the Iberian Peninsula. Especially wind but also solar (PV and CSP) generation lead to low and even negative residual load values.

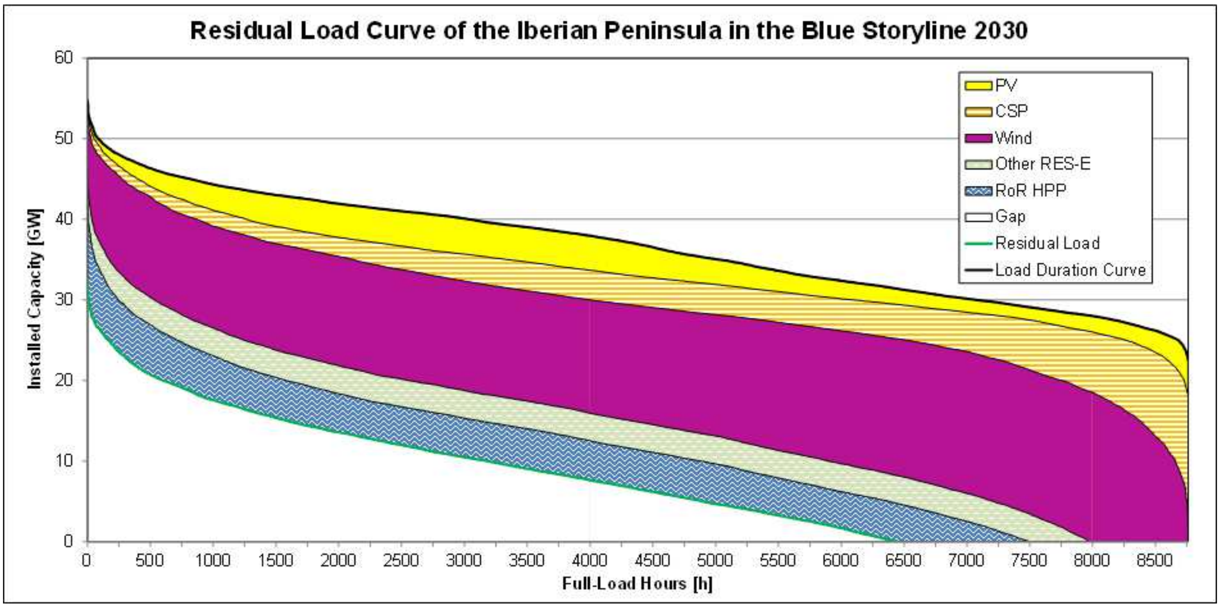

Figure 41: Load duration and residual load curve for the Iberian Peninsula in the *Blue* storyline in the year 2030 (Source: own calculations)

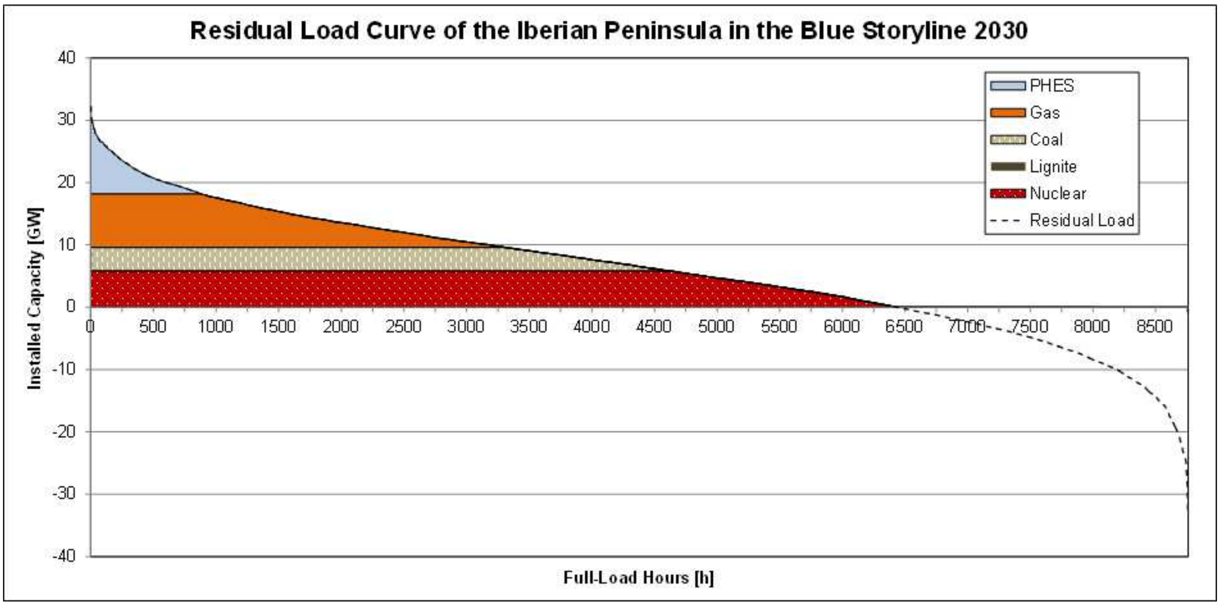

Figure 42: Coverage of the 2030 residual load of the Iberian Peninsula with existing thermal power plants and PHES in the *Blue* storyline (Source: own calculations)

Further on, it can be seen that sufficient (thermal) power plant capacity is available in the region (i.e. no capacity gap between supply and demand) in 2030 (cf. Figure 42) – actually there is an overcapacity of more than 34 GW of gas-fired TPP in the Iberian Peninsula. This fact has two reasons: On the one hand, high RES-Electricity deployment in the region and, on the other hand, large amounts of still existing TPP in the year 2030 – especially 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)) is perfectly qualified to balance electricity systems and to provide reserve capacities in electricity systems with high shares of variable RES-Electricity generation. These gas-fired generation technology types are needed and, alongside bulk electricity storage technologies (e.g. PHES, CAES, etc.), 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 a gas pipeline like "*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.

For the optimization of the PHES system operation in the Iberian Peninsula in the year 2030 the maximum storage capacity was set to 2,000 GWh[39] and the maximum turbine / pumping power was set to 14 / 13 GW. The results of the optimization algorithm are shown in Figure 43. It can be seen that the residual peak-load in the Iberian Peninsula can be lowered to about 18 GW in the year 2030. Further on, more than 90% of the domestic excess RES-Electricity generation can be integrated in the electricity system by the PHES system. For a full RES-Electricity integration a higher pumping power would be needed. Due to the PHES system operation the maximum full-load hours of TPP are increased to about 7,250 hours. For about 1,100 hours the residual load is reduced to zero by the PHES system – the electricity system is balanced with 100% RES-Electricity generation.

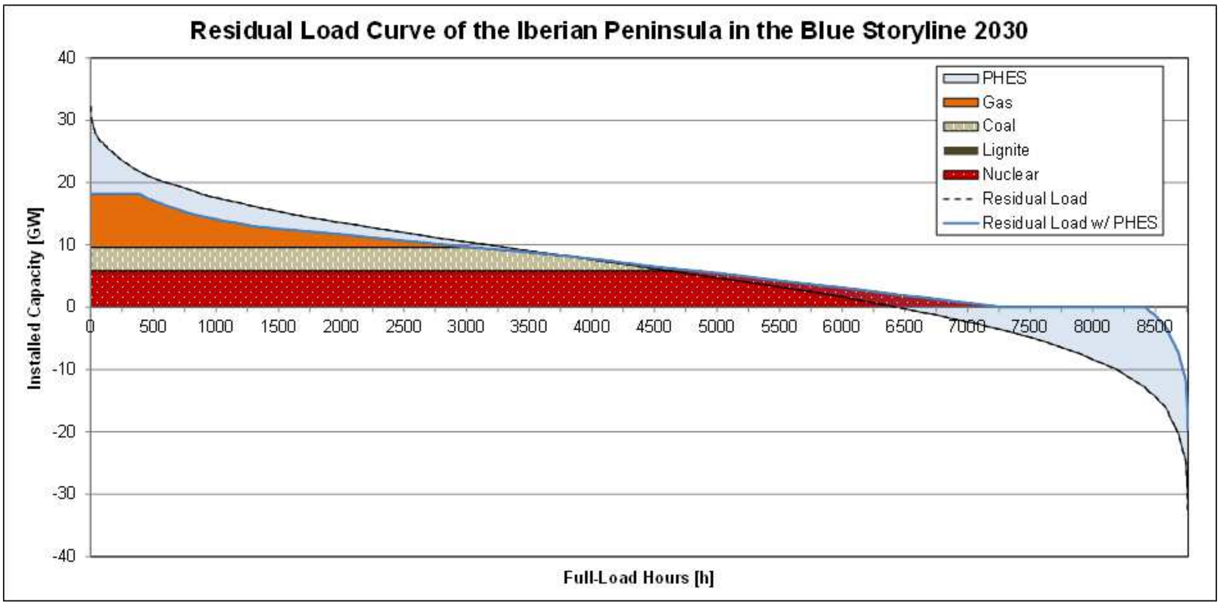

Figure 43: Coverage of the 2030 residual load after PHES optimization in the Iberian Peninsula with existing thermal power plants in the *Blue* storyline (Source: own calculations)

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[39] Cf. EURELECTRIC, 2011a (pp. 16-19)

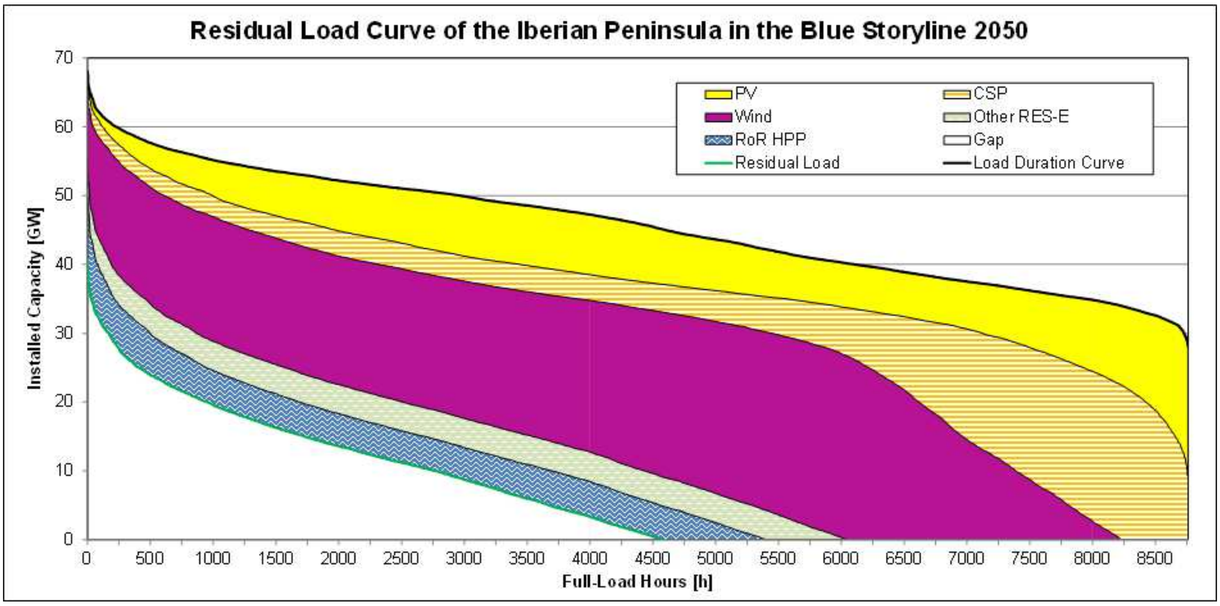

Figure 44: Load duration and residual load curve for the Iberian Peninsula in the *Blue* storyline in the year 2050 (Source: own calculations)

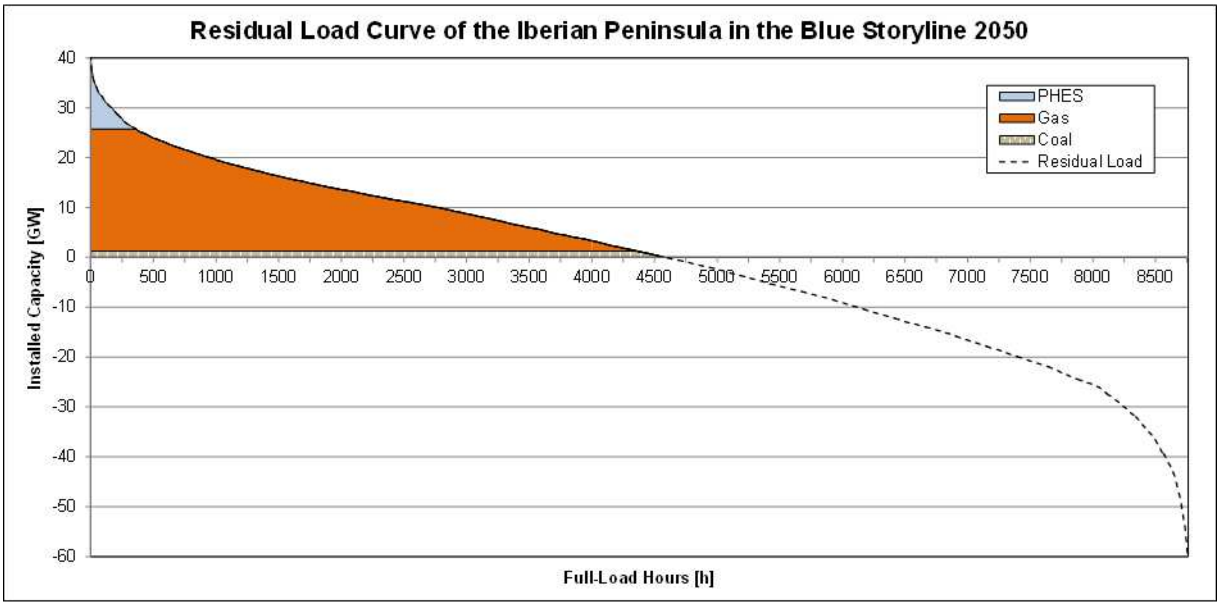

Figure 45: Coverage of the 2050 residual load of the Iberian Peninsula with existing thermal power plants and PHES in the *Blue* storyline (Source: own calculations)

RES-Electricity feed-in exceeds electricity demand about half the time of the year 2050 in the Iberian Peninsula - especially additional solar generation units contribute to this. Until 2050 a further increase in RES-Electricity deployment leads to even lower maximum full-load hours for TPP in the Iberian Peninsula (cf. Figure 44 and Figure 45). However, CSP plants equipped with thermal energy storage systems could, to some extent, also operate in a more flexible way[40], i.e. as dispatchable power plant comparable to e.g. gas-fired TPP. When operating CSP plants like TPP, i.e. taking them out of the calculation of the residual load in Equation 6, the maximum full-load hours of TPP can be increased again to about 6,500 hours.

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[40] See e.g. IEA, 2011a.

As already seen in the results of the year 2030, sufficient generation capacities (gas and PHES power plants) are available in the system to cover the residual load also in 2050. Again there is an overcapacity in the region – about 9 GW of gas-fired TPP.

For the PHES system optimization in the year 2050 the turbine as well as the pumping power were increased by 1 GW to 15 and 16 GW respectively. The storage capacity was held constant indicating an upgrade of existing PHES facilities in the Iberian Peninsula between 2030 and 2050. Coverage of the 2050 residual load after PHES optimization in the Iberian Peninsula with existing thermal power plants is depicted in Figure 46. Again the residual peak-load is lowered to about 25 GW. Due to the low residual load in the Iberian Peninsula in the year 2050 in general, also the remaining residual load is curtailed to a large extent – maximum full-load hours of TPP are therefore further reduced to about 4,000 hours. About 60% of the surplus RES-Electricity generation can be integrated in the Iberian Peninsula's electricity system by the PHES system. However, large amounts of excess RES-Electricity generation remain – about 26 TWh in the year 2050. This indicates that there is an additional need for pumping power in the region.

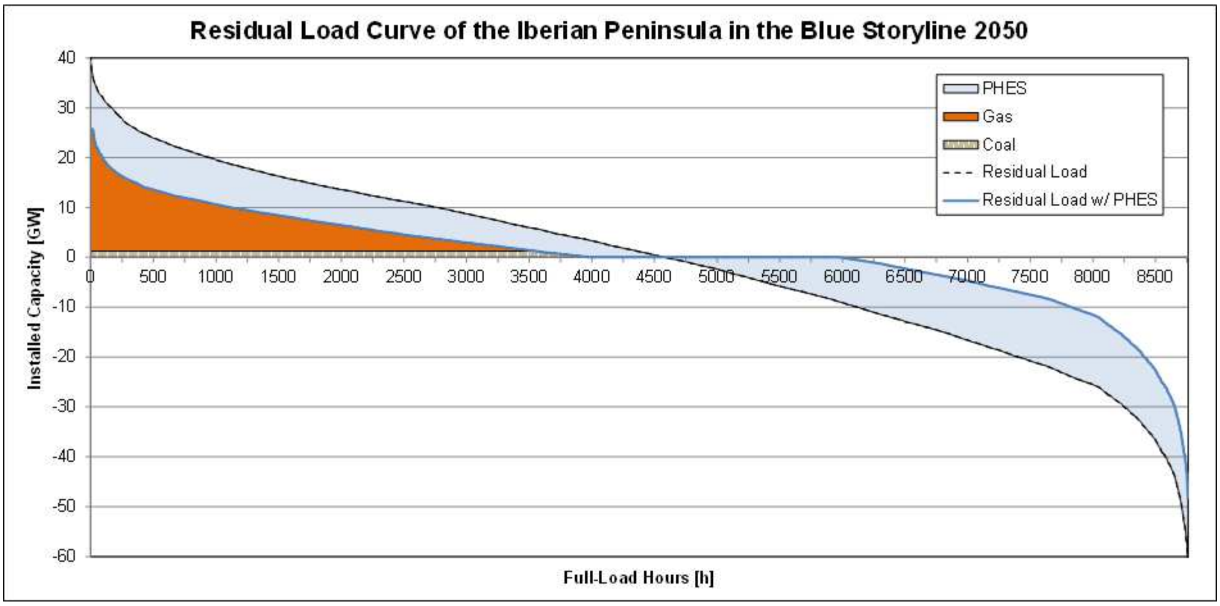

Figure 46: Coverage of the 2050 residual load after PHES optimization in the Iberian Peninsula with existing thermal power plants in the *Blue* storyline (Source: own calculations)

4.4.5 Discussion of the European Electricity Market Region Results

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 by 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 flexible thermal power plants.

Only some European regions have 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 *Blue* storyline RES-Electricity feed-in exceeds electricity demand for some time of the year 2050 in several of the analysed regions. This surplus RES-Electricity 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, especially 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.

4.5 Role of Cross-border Transmission Grid Expansion and Extreme Weather Events in the European Electricity Market Regions

The contribution of possible future transmission grid expansion between neighbouring European electricity market regions for better matching variable RES-Electricity generation, bulk EST / other flexible electricity generation technologies and load centres (e.g. balancing “stressed” continental European electricity systems with bulk storage energy from PHES from the Alps) is qualitatively discussed in Figure 47. Furthermore, the contribution of existing and new PHES and flexible thermal power plant units within a region and the management of extreme weather events (e.g. high correlation / concurrency of wind across Europe) within a region and between regions are assessed.

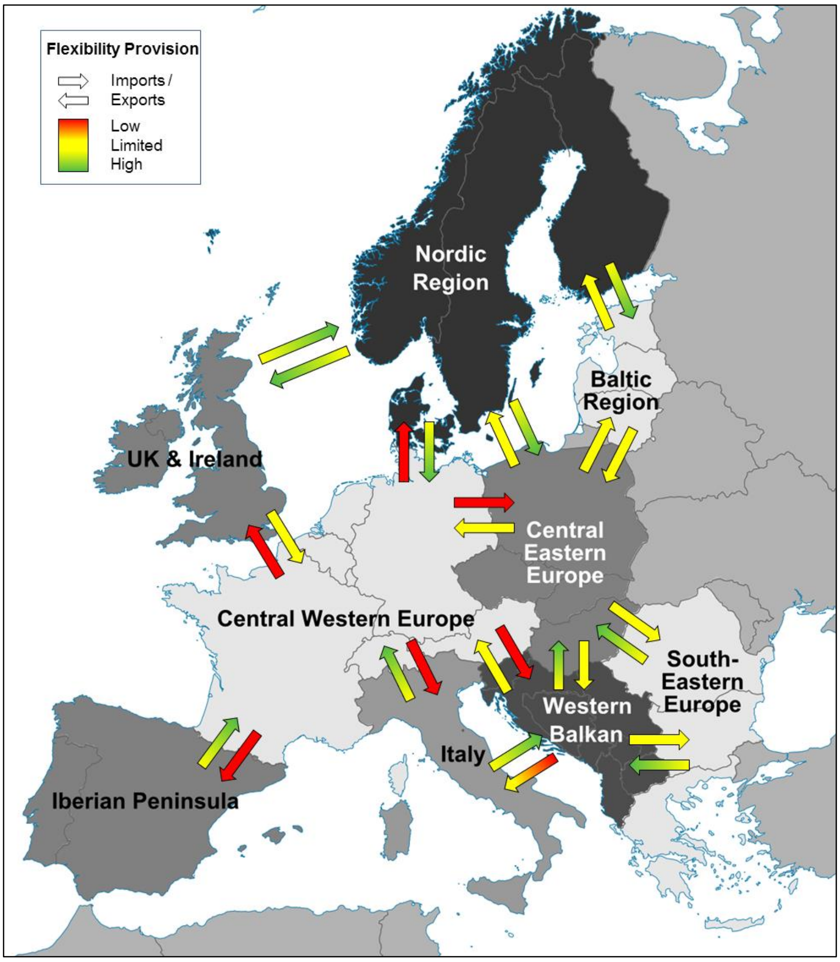

Figure 47: Contribution of transmission grid expansion for mitigation of variable RES-Electricity generation (e.g. wind) within the regions

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 (cf. red export-arrows of the CWE region in Figure 47). However, imports from the Nordic region, the Iberian Peninsula and also Italy could help mitigating the effects of variable RES-Electricity generation in the CWE region in case of significant transmission grid expansion and negative correlation of wind. In case of moderate transmission grid expansion or positive correlation of wind between the regions, the contribution from these regions is limited (cf. yellow-green import-arrows of the CWE region in Figure 47). Also imports of flexibility from the Central Eastern Europe (CEE), Western Balkan and UK & Ireland region are only limited (even in case of significant transmission grid expansion and negative correlation of wind, cf. yellow import-arrows of the CWE region in Figure 47). Below, Table 7 explains the situation for the CWE region in detail. For better readability, the result tables for the remaining regions can be found in the Appendix A.8.

In addition to the information given in Figure 47 (i.e. contribution from outside and contribution to other regions), Table 7 also indicates that new and existing PHES and thermal power systems have a high contribution to mitigating the effects of variable RES-Electricity generation in the CWE region.

Table 7: Contribution of transmission grid expansion for mitigation of variable RES-Electricity generation (e.g. wind) within the CWE region and management of extreme weather events

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")	
	Contribution in CWE		*Transmission Expansion to the Nordic Region*		*Transmission Expansion to the Nordic Region*	
	PHES	Thermal	Moderate	Significant	Moderate	Significant
CWE	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)

The Western Balkan region could only provide limited flexibility to the CWE and the South-Eastern Europe (SEE) region. Due to currently low transmission capacity between Italy and the Western Balkan region, a significant transmission expansion is necessary for reciprocal flexibility provision between these two regions.

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 flexibility from gas-fired thermal power plant units.

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 significant transmission grid expansion and 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 and negative correlation of wind. If additional generation capacities are needed, UK & Ireland could contribute with their flexible thermal power plant portfolio.

For the remaining European electricity market regions the following can be observed: Since Italy's electricity system is very similar to the Iberian Peninsula's (i.e. high shares of gas-fired thermal power plants and PHES systems), Italy could export flexibility to CWE and the Western Balkan region. Because of high shares of PHES capacities in its electricity system, also the South Eastern Europe region could export flexibility to its neighbouring regions. On the contrary, due to low overall installed power plant capacities, the Baltic region's flexible power plant portfolio is only of minor importance in a European context. In the UK & Ireland region PHES systems will have a little contribution to the electricity system only, because of low future PHES potentials. Nevertheless, the UK & Ireland region could provide flexibility from gas-fired thermal power plant units to neighbouring regions.

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-Electricity feed-in in the future. Only in the Iberian Peninsula and Italy 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.

5 Selected Case Study Results from the Analysis of the Heat / Gas Sector in the Yellow Storyline

Out of the four different storylines, the *Yellow* storyline is selected for representing the analysis in the heat / gas sector. The main reasons for choosing *Yellow* over the other storylines is that it is the most "*tricky*" future for heating / gas systems: there is low demand growth and high public acceptance for decentralised (renewable) heating systems (heat pumps, solar thermal systems, biomass, etc.), leading to problems for (residential) gas / district heating suppliers in finding proper loads and use for the given (gas) infrastructure. Looking at the development in recent years, it also seems that *Yellow* is the most realistic storyline for some regions, i.e. energy-efficient buildings with decentralised (renewable) heating systems became more or less standard in Austria. Reasons for this development might be growing awareness about uncertainties in the gas price development and gas availability (e.g. dispute between Russia and Ukraine in winter 2009 / 2010). Further on, the heat sector is generally much easier to understand than the electricity sector, making it simpler and more convenient for people to invest in heating and energy efficiency technologies.

The results of the analysis of the heat / gas sector are presented also country wise (i.e. Austria, Serbia and Spain) in the following sections. For each country the status quo of the heat / gas sector is briefly summarized before presenting and discussing the respective results of the analysis.

5.1 Austria

5.1.1 Status Quo of the Austrian Heating Sector

In order to give an overview about the current situation in the heating sector in Austria, Table 8 shows the heating technologies used in domestic households in the heating season 2009 / 2010 and 2003 / 2004 in comparison. The trend of heating domestic households in Austria between the two heating seasons clearly shows a decrease in households using coal-fired and oil / liquid gas heating systems (decline of about 42,000 and 170,000 households respectively). There are only small changes in the domestic use of natural gas and direct-electricity heating, while wood-based heating systems, district heating as well as solar thermal / heat pump-systems increased considerably. Therefore, it can be seen that also in the past few years a shift away from fossil-fuel heating systems has been made in Austria.

Table 8: Comparison of heating fuels / technologies used in Austrian households in 2003 / 2004 and 2009 / 2010 (Source: Statistik Austria, 2013)

Heating Fuels used in Households	**No. of Households 2003 / 04**		**No. of Households 2009 / 10**	
Wood, wood chips, pellets, briquettes	640,945	19%	719,671	20%
Coal, coke, coal briquettes	67,831	2%	24,048	1%
Heating oil, liquid gas	908,056	26%	738,666	21%
Electricity	267,329	8%	259,326	7%
Natural gas	903,549	26%	938,203	26%
Solar thermal, heat pumps	25,825	1%	88,340	2%
District heating	616,186	18%	826,350	23%
Total	**3,429,721**	**100%**	**3,594,604**	**100%**

5.1.2 Analysis of the Austrian Heating Sector

RES-Heating Deployment in the Yellow Storyline for Austria

In a first step of the analyses of the Austrian heating sector up to 2050, RES-Heating deployment scenarios for the four different storylines have been derived based on the study "*Heating 2050*" (Biermayr et al., 2009), which analysed heating and cooling in the Austrian residential and tertiary sector up to the year 2050. "*Heating 2050*" methodically is based on the application of a disaggregated simulation model with an economical optimization algorithm, enabling the choice of different target functions. The Austrian building stock is implemented in this model, including different options of heat supply systems and technologies, fuel switching etc. These settings allowed the simulation of the future building stock and space heating development in Austria up to the year 2050 in different scenarios on an annual basis.

The outcomes of the "*business-as-usual*" (BAU) scenario of the "*Heating 2050*" study were adopted for the *Red* storyline of the analysis. The *Red* storyline also set the starting point to establish and argue the starting points of the other storylines. Based on own assumptions according to the corresponding storyline descriptions, technological development and ambitions in energy efficiency implementation in Austria up to 2050, the settings of the remaining storylines were derived from those of the *Red* storyline.

In Figure 48 the results of end-use energy demand in the residential heating sector in Austria are exemplarily presented for the *Yellow* storyline up to 2050[41]. It can be seen that the residential heating demand decreases significantly in the *Yellow* (and similarly in the *Green*) storyline in the next decades up to 2050 – in total demand is reduced by about 90 PJ. Moreover, in all four storylines oil heating systems are increasingly replaced by RES-Heating technologies; finally resulting in a complete phase out of oil heating systems in the Austrian residential sector in 2050 in *Yellow* (and also in *Green).*

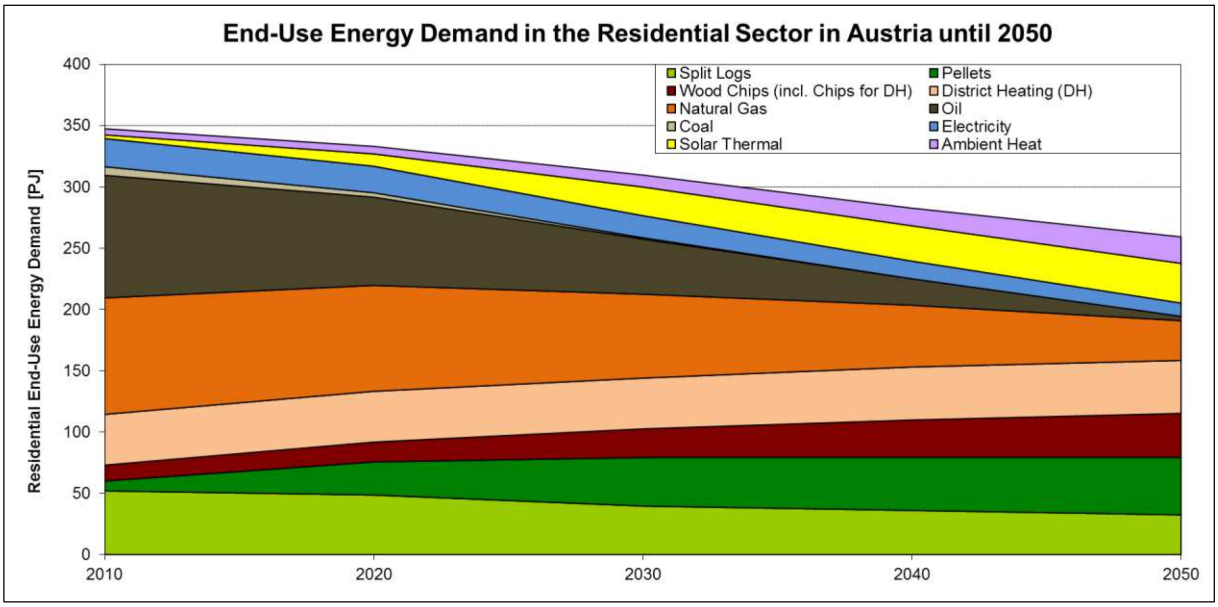

Figure 48: End-use energy demand in the residential heating sector in Austria from 2010 to 2050 in the Yellow storyline (Source: see text above)

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[41] See Appendix A.9 for the results in the residential heating sector of the remaining storylines in Austria.

Further on, it can be observed that gas heating systems in Austria stay more or less constant (*Red / Blue*), decrease (*Yellow*) or even phase out (*Green*) until 2050. Therefore, no extension of the gas distribution grid in Austria is needed in the future to supply the residential sector. Even more, in the *Green* storyline, where also gas heating completely phases out in the residential sector in Austria until 2050, the question arise, what to do with the existing, but obsolete gas distribution grid in the residential sector in Austria in 2050.

Also residential district heating (DH) does not indicate any increase in the four different storylines up to 2050. The reason for this is that large-scale district heating grids - supplied by heat from CCGTs, waste and / or biomass combustion technologies – are limited in its implementation to niche markets like dense areas and municipalities / cities. Small-scale grid-connected biomass heating shows moderate / significant extension in the different storylines until 2050, but it is also limited to dense areas and municipalities / cities. Nonetheless, competitors for both heating grid systems are energy efficiency (see section 6.2) and also innovative heating technologies such as solar thermal collectors, ambient heat and heat pump systems.

Economics of different RES-Heating Technologies

In a second and final step of the analysis of the Austrian heating sector, an economic trade-off analysis of the different residential RES-heating technologies has been conducted on a disaggregated level with the *eTransport* model (see section 3.2.1 for a comprehensive description of the *eTransport* model and Appendix A.4 for the setup of the Austrian case study analysis).

Figure 49 presents the different "phase-in" levels of various residential RES-Heating technologies (and combinations of them like local stand-alone biomass combined with solar thermal) in the four different storylines. The gas price is used as the varying sensitivity parameter.

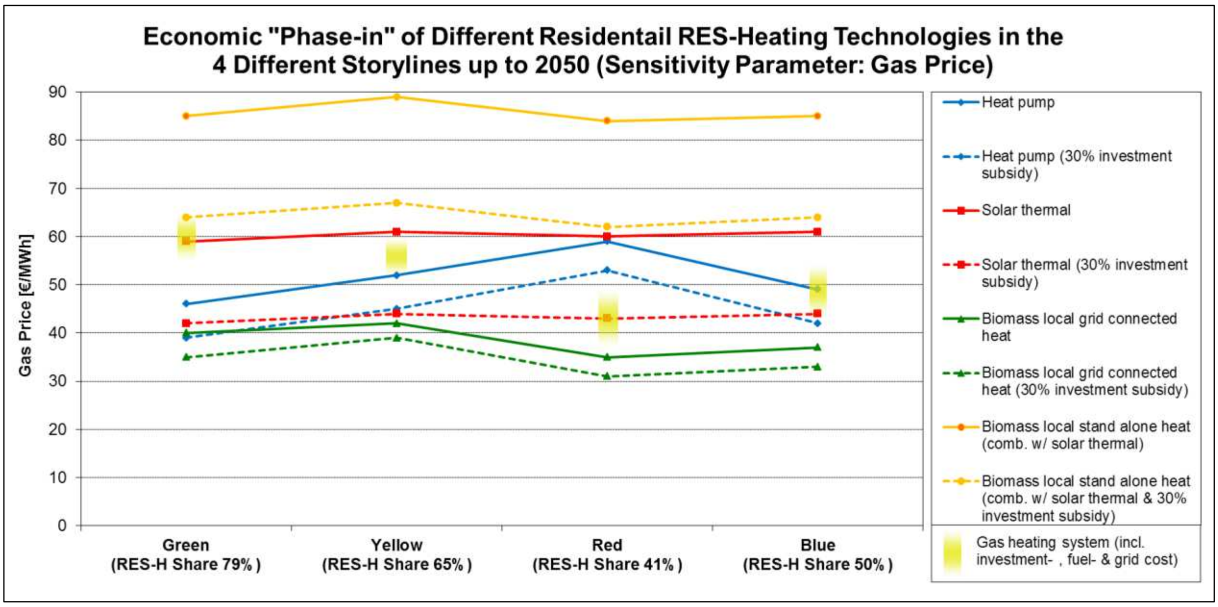

Figure 49: Different "phase-in" levels of the various residential RES-Heating technologies in the four different storylines (Source: own calculations)

In Figure 49 it can be seen that local grid connected biomass heating systems are the cheapest RES-Heating options (also cheaper than new gas heating systems) in all of the four storylines. Grid connected biomass is followed by heat pumps. This is also true for this heating technology for all four storylines for the period 2010–2050. In a next step of the analyses, the effect of an investment subsidy of 30% for the different RES-Heating technologies is studied in order to get an idea of the economics of solar thermal heating systems with and without combinations with other heating systems. Whereas the grid-connected biomass technology phase-in level can only be reduced marginally, subsidies on solar thermal installations (also in combination with stand-alone biomass) significantly reduce its phase-in level and can contest heat pumps and also gas heating systems.

5.1.3 Discussion of the Austrian Results in the Heating Sector

Figure 50 below summarizes the main structural aspects derived from the scenario analyses of the residential heating sector in the four different storylines in Austria up to 2050. Special attention is given to the discussion of the results of the *Yellow* storyline.

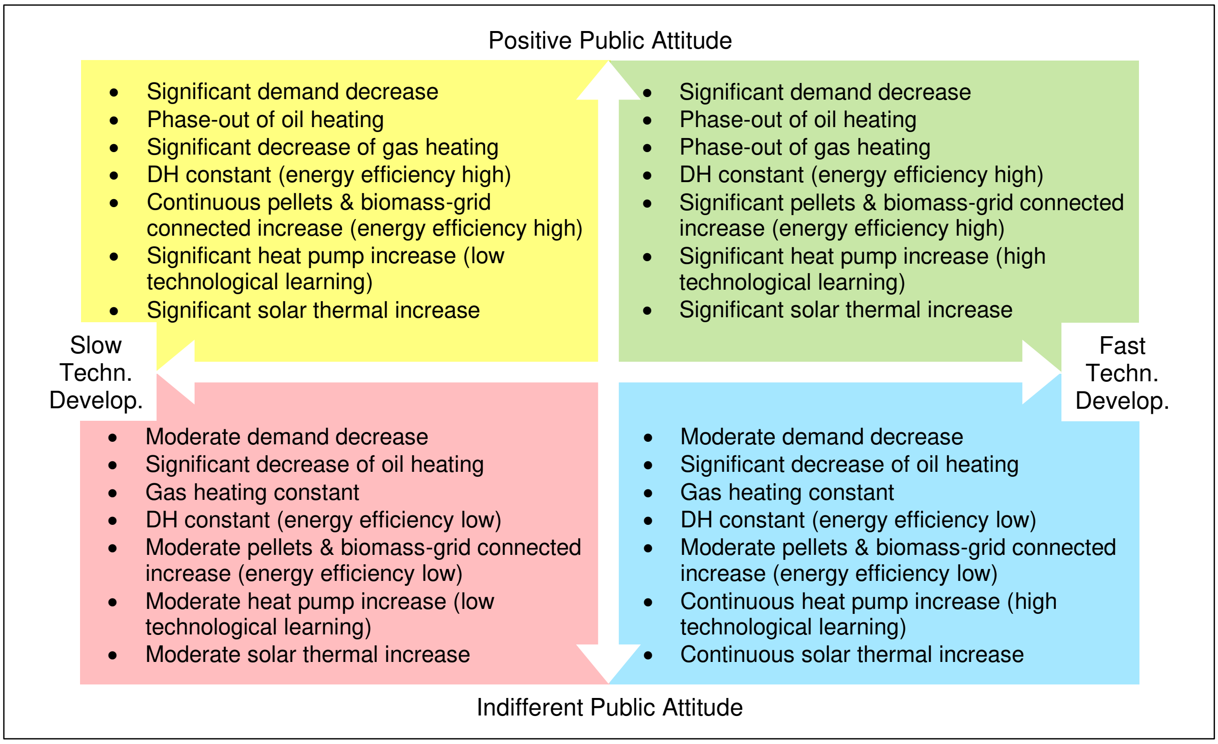

Figure 50: Structural aspects in the residential RES-Heating sector in the four different storylines in Austria up to 2050

The *Yellow* storyline in Austria is characterized by a significant end-use energy demand decrease in the residential heating sector. Fossil-fuel heating systems decrease significantly (or in case of oil heating even phase-out) and are increasingly replaced by RES-Heating technologies (e.g. biomass / pellets, solar thermal, etc.). DH stays constant over the analysed period in the *Yellow* storyline due to high energy efficiency and because Austrian dense areas and municipalities / cities were already developed by DH in the past.

5.2 Serbia

5.2.1 Status Quo of the Serbian Heating Sector

In the Republic of Serbia the period of the most intensive housing stock growth of residential buildings was in the 1970s and 1980s. Due to bad thermal quality, these buildings are characterized by a high final / heating energy consumption and oversized heating installations and boilers, or heating substations if connected to the district heating systems. In general, the age of the Serbian dwellings is high (59% of the dwellings were built before 1962, and only 2% in the period from 2004 to 2008), leading also to high final end-use energy needs. The average specific final energy consumption for heating and hot water supply in Serbia is estimated to about 220 kWh/m^{2}a, which is much higher than the EU average of 138 kWh/m^{2}a (Republic of Serbia, 2010).

Dwellings are heated in the Republic of Serbia with the means of unitary heating appliances (gas, wood, coal and a particularly high share of direct electric heating), individual boiler houses and district heating systems. According to Glavonjić, 2011, 23.2% of the total number of households in Serbia used district heating systems, 25.3% electricity, and 10.6% gas for heating purposes in the heating season 2010 / 2011. Further on, the majority of households (40.9%) used solid fuels such as wood, coal, briquettes, pellets, agricultural residues, and combinations of solid and other fuels. The comparatively high use of electricity for heating results from relatively low electricity prices.

5.2.2 Analysis of the Serbian Heating Sector

According to the Statistical Office of the Republic of Serbia (Statistical Office RS, 2013) the household sector accounted for 2.545 Mtoe or approximately 29% of the total final energy consumption in Serbia in 2011. The main energy source in the household sector was electricity (with about 50%) – however, on the basis of available data it is not possible to distinguish between electricity for heating and other purposes (e.g. lightning, electric household appliances, etc.). Another difficulty for the analysis is the consumption data relating to biomass, which only covers firewood from registered production. According to Glavonjić, 2011 the real use of biomass / forest wood for heating is much higher (especially in rural areas) – however, no data is available. Due to these reasons[42], the analysis of the Serbian heating sector in the *Yellow* storyline is done in qualitative terms only.

The most challenging effort in the Serbian heating sector in the next decades will be a reduction of the specific final energy consumption in the household sector. In the *Yellow* storyline buildings with higher energy efficiency are going to replace the pre-1962 dwellings and insulations of residential buildings improve (e.g. replacement of outside doors, windows and overall thermal insulation) respectively.

Currently there is a high and inefficient use of electricity for heating and cooling in households (e.g. air-conditioners even on face walls of residential buildings, inefficient heating of sanitary water, etc.). In the *Yellow* storyline a reduction of the electricity consumption for heating purposes takes place by using heating equipment of higher energy efficiency (e.g. heat pumps) but also by substituting direct electric heating with other

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[42] Further on, historical data is only available for Serbia and Montenegro together.

technologies like solar thermal collectors. In order to facilitate this transition, it is also necessary to make corrections to the electricity tariff system, e.g. higher electricity prices for households.

Biomass is already being used extensively – however, currently more forest wood than forest residues and agricultural waste is being used. Furthermore, many households are using inefficient stoves / ovens. The increased environmental awareness in *Yellow* leads to a continuous but more efficient use of biomass (e.g. pellets) in the household sector.

District heating will also continue to be an important part in the heating of buildings in dense areas (cities) in *Yellow*. However, low-efficient coal-fuelled heating plants will be replaced by gas-fuelled CHP-plants with higher overall efficiency.

The use of coal and fossil-fuels for heating purposes will decrease in *Yellow* due to positive public attitude towards renewable technologies. Due to good solar potential, especially solar thermal systems will be increasingly deployed in Serbia.

5.2.3 Discussion of the Serbian Results in the Heating Sector

Like the electricity sector, also the Serbian heating sector is currently in transition towards a more sustainable future but has to deal with "historical legacy issues" (i.e. low energy standards in the majority of the Serbian building stock). The Energy Sector Development Strategy of the Republic of Serbia until 2015 (adopted 2005) already set a starting point in this development, recognizing energy efficiency as a main priority. Also the first Energy Efficiency Plan of the Republic of Serbia for the period from 2010 to 2012 (Republic of Serbia, 2010) was recently established, which foresees the introduction of an Energy Efficiency Fund.

However, there are many obstacles in renovation and retrofitting procedures in the household sector in Serbia. On the one hand, the socio-economic status of many parts of the population may not provide an option for retrofitting. On the other hand, the people’s awareness about energy efficiency is not very distinctive today.

Along with the adoption of reliable plans for financing energy efficiency in households and buildings, there may be a need for additional measures to be implemented in order to reach the outlined *Yellow* storyline (e.g. intensive awareness boosting campaigns on rational use of energy etc.).

5.3 Spain

5.3.1 Status Quo of the Spanish Gas Sector

Natural gas is one of the most important fossil fuels in Spain (after oil) and provided 24.4% of total primary energy supply (IEA, 2013). Gas supply in Spain is much diversified: there are 10 countries supplying LNG to Spain and four countries with direct pipeline connection. In 2011, LNG accounted for 66% of total gas imports – LNG has been allowing Spain to strongly diversify its imports: In 2008, gas imports to Spain mainly came from Algeria (32%), followed by Nigeria (20%), Qatar (13%), Trinidad and Tobago (12%), Egypt (11%) and Norway (7%), while in 2001 Algeria accounted for 70% of gas imports (Frías et al., 2010).

Regarding infrastructure (see Figure 51), the Spanish gas transmission grid is interconnected with Portugal, France, Morocco and Algeria. Currently, there are seven LNG terminals in operation in Spain: Barcelona, Sagunto, Cartagena, Huelva, Mugardos, El Musel and Bilbao (cf. Figure 51). Additionally there are four underground gas storages (Gaviota, Serrablo, Yela and Marismas y Rincón) with a total capacity of 2.7 bcm. Current capacity of underground gas storage facilities accounts for about 12% of the annual Spanish gas demand in 2011 (IEA, 2013).

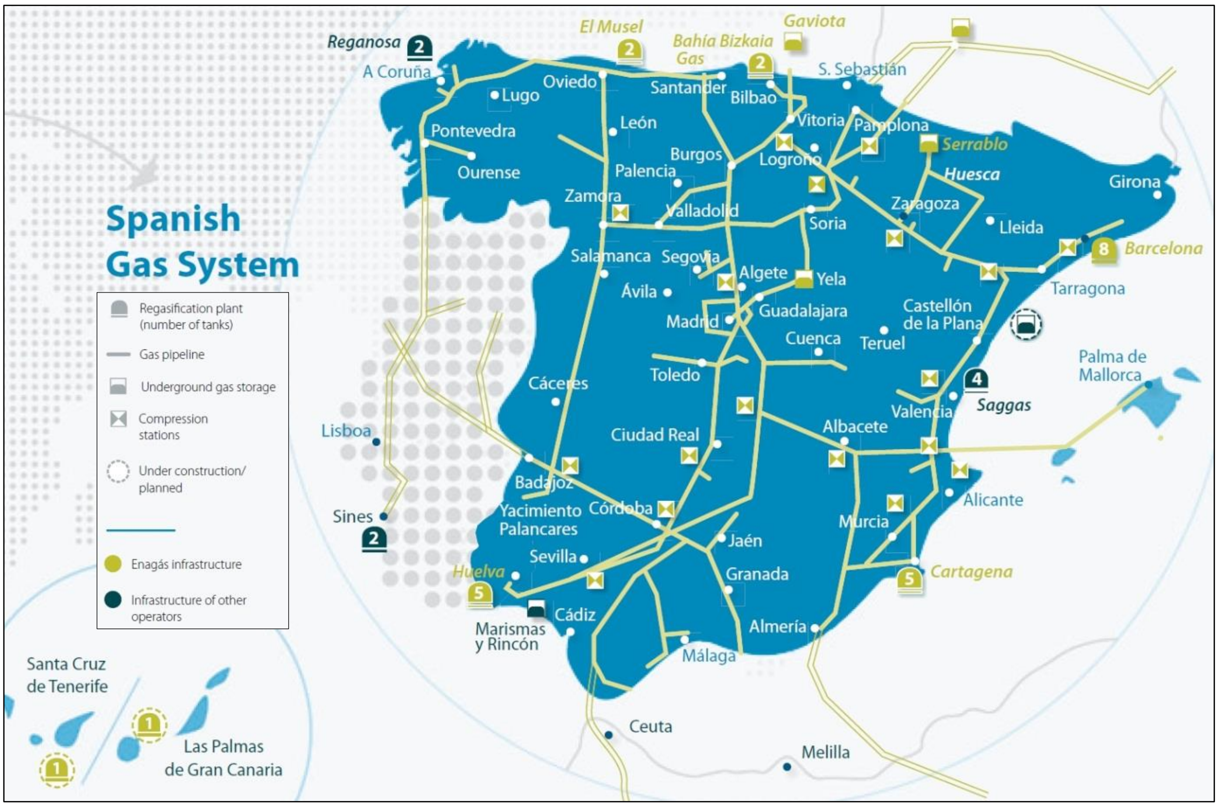

Figure 51: Map of the Spanish gas system in 2012 (Source: ENAGAS, 2013)

The Spanish primary energy demand of gas amounted to 374 TWh in 2011 (CNE, 2012). Natural gas demand can be divided into two main categories, namely the conventional and the electricity sector. The conventional gas sector comprises gas demand from the residential, services and industrial sectors[43] (also including gas consumption of cogeneration units). Gas demand in the electricity sector is mainly driven by the Spanish CCGTs. From 2001 to 2008, the annual gas demand in Spain grew about 113%, from 211 TWh to 450 TWh. This growth was – in great part – due to the expansion of electricity generation with CCGTs. The share of the electricity sector on the gas demand grew from 6% to 42% in the same time frame. However, since 2008 the Spanish gas demand is decreasing continuously (CNE, 2012).

5.3.2 Analysis of the Spanish Gas Sector

As previously mentioned, the analysis of the Spanish heating system was not performed by the author himself, but, in order to draw overall results and to make comparisons between different heating systems, the modelling results of the Spanish system are also included in this thesis. The modelling results were taken from Frías et al., 2010 (see also section 3.2.2).

The analysis in the Spanish case study has not been restricted to detailed considerations of RES-Heating only, but the role of gas supply and corresponding gas infrastructure needs in the domestic and industrial sector also have been investigated in detail. Moreover, the Spanish analysis in this context assumes that future gas infrastructure needs have the following drivers: (i) RES-Electricity penetration, significantly impacting the production of gas-fired thermal electricity generation, and (ii) domestic and industrial gas consumption meeting different end-uses.

Currently, almost all of Spanish domestic gas consumption is demanded by household gas heating systems; they are, however, assumed to be replaced by heat pumps in the *Green* and *Blue* storyline. In the *Red* and also the *Yellow* storyline domestic gas consumption still increases (and corresponding grid infrastructure is built) until majority of Spanish households have access to gas.

Using year 2010 as a reference, Figure 52 (right) presents a comparison of the maximum and / or additional gas supply capacity required in Spain in the four different storylines in 2020, 2030 and 2050. This comparison also takes several important gas network design criteria into consideration, including a 10% supply margin required for the secure operation of gas networks. Interestingly, compared to the status quo in 2010, in several of the four storylines there is no need to significantly extend the gas grid infrastructure network in Spain in the near future. Moreover, gas supply can be met with the existing gas infrastructure in the next 10–15 years.

In the medium to long-term, however, the *Red* storyline indicates steadily increasing gas consumption and, subsequently, gas grid infrastructure capacity and investment needs (also due to a higher share of CCGT units in operation for electricity generation and low environmental concern in this storyline). Also in the *Blue* and *Yellow* storyline further gas infrastructure capacity and investment expansions are needed (see Figure 52 (left) in detail) beyond 2030. However, beyond 2040 some of these expansion measures are supposed to remain excess capacities in the long-term future (2050 and beyond) again; simply because gas demand is decreasing or remains stable in the *Blue* and *Yellow* storyline respectively beyond 2040. And finally, the *Green* storyline does not expect any gas infrastructure expansion

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[43] Conventional gas demand in Spain grew from 199 TWh to 266 TWh from 2001 to 2011. Almost all domestic consumption of natural gas comes from household heating, while industry is the largest gas user.

measures any more. Moreover, in *Green* in the medium to long-term parts of the already existing gas infrastructure are simply obsolete.

Figure 52 (right), finally, presents total cumulated gas infrastructure cost over RES-Electricity shares. As already stated above, *Green* does not expect any investments any more. On the contrary, lower RES-Electricity penetration certainly requires new investments in gas capacities and infrastructures, being very high in the case of low technical developments and low “green” conscience (*Red* storyline).

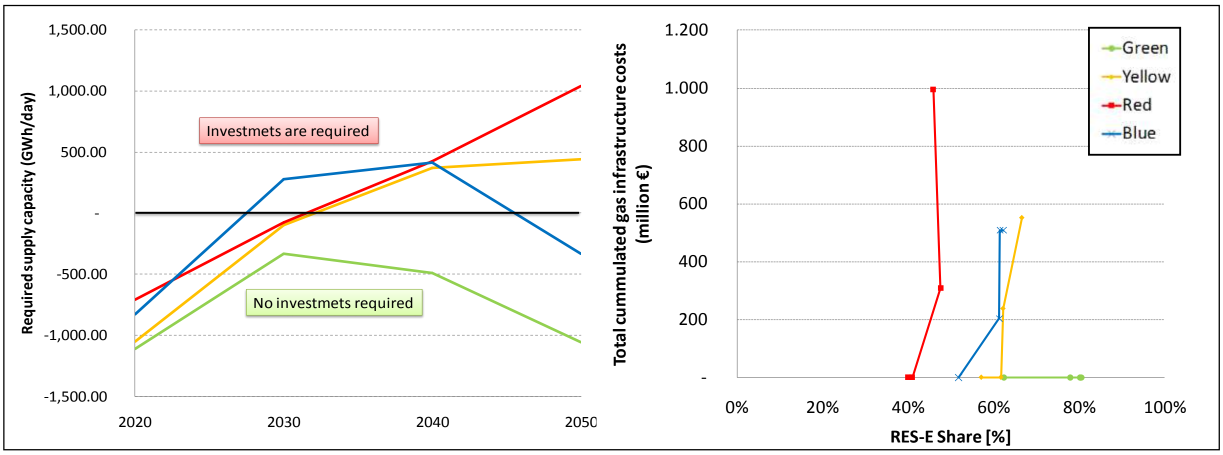

Figure 52: Required gas capacity over time (left) and total cumulated gas infrastructure costs over RES-shares (right) in the four different storylines in Spain from 2030 to 2050 (Source: Frías et al., 2010)

5.3.3 Discussion of the Spanish Results in the Gas Sector

Summing up, the investment required in Spanish gas infrastructures will depend to a large extent on the RES penetration level, mainly due to the impact of RES-Electricity generation on the reduction of gas-fired power plant production. If the RES-Electricity generation share is over 70% (cf. Figure 52 (right)), then it is not expected that there will be a need to further develop the existing gas grid (excluding upgrade / replacement of the existing infrastructure). Therefore, a common energy strategy including the development of gas infrastructures together with the RES-Electricity deployment is very important for Spain.

However, increasing the capacity of the gas transmission interconnection with Europe (through France) has advantages in any future scenario. In case of low RES-Electricity penetration, Spain could benefit from the access to French underground gas storage facilities and also from higher importing capacity, increasing the security of supply. In case of high RES-Electricity penetration and, therefore, low gas demand, Spain could use the expanded interconnection capacity and gas infrastructure to become a gas-hub in Europe.

6 Synthesis of Results

The results from the case studies indicate that all European countries / regions are able to integrate larger shares of renewable energy sources, but non-RES sources will also be present in varying degree in most regions. However, very different infrastructures will be needed at regional (and also trans-national) level dependent of the "*type of future*" in the different storylines. Especially futures like *Green* and *Blue* will require other infrastructure development paths compared to current strategies of regional security of supply and centralized generation. The following bullets highlight the main characteristics of each region having been comprehensively analysed in this thesis:

- **Austria** (CWE region)
  - Already high national shares of RES;
  - Only solar PV resources still available beyond 2030, most other hydro and wind potentials already exploited;
- **Serbia** (Western Balkan region)
  - Abundant local lignite resources utilized in all storylines together with hydro power;
  - Due to current development, major resources are assumed to be utilized before 2030;
  - Current under-investment in infrastructure and low purchase power among consumers; mainly development of small-scale RES generation and storage foreseen, combined with demand side management and smart grid technologies at low cost;
  - Fossil generation present in all storylines, based on local lignite and CCGT connected to the planned South Stream gas pipeline project;
- **Spain** (Iberian Peninsula)
  - Large potential for solar and wind generation;
  - Challenges related to variability and balancing of RES-Electricity; parallel strategy of gas-fired CCGT units;
  - Stronger interconnection with rest of Europe (France) needed;
  - No further need for domestic gas investments if RES-Electricity shares exceed 70%;
  - Trans-national gas interconnections with Europe advantageous in all storylines;

6.1 Electricity Sector

The outcomes of the three in-depth scenario studies on grid infrastructure integration of RES-Electricity generation technologies in different European countries and regions teach us a variety of lessons. In many cases today, RES-Electricity in Europe is integrated in the energy system on a project-by-project basis and not according to an overall plan, while many of the case studies show that the full potential of a region can be exploited only in a trans-national context. To obtain the most effective utilization of RES from a Pan-European perspective (in terms of reduction of CO_2 emissions, minimum economic costs and sufficient security of supply) and to be able to develop infrastructures in the most appropriate way, coordinated planning is important. The regional case studies in this thesis have shown that the future may look very different depending on which RES sources are utilized for energy production and also in which sequence they are included in the energy system.

In the following, the most important criteria for successful grid integration of RES-Electricity generation technologies are briefly outlined:

- Due to the fact that natural resources for RES-Electricity generation are site specific in many cases, *"artificial borders" (political, institutional, etc.) shall be avoided wherever it is possible;* simply because the operation of electricity systems is governed by physical laws.
- *Utilize economies of scale of RES-Electricity generation both in a regional and in a Pan-European context*; i.e. the most attractive sites shall be chosen first. In case of low electric load density in an area or region also transmission connection to fitting load centres with sufficient load density outside the region shall be considered.
- *Develop inter-regional (European-wide) business and cost remuneration models for transmission investments*, if they are needed to utilize low-cost RES-Electricity generation and to fulfil other energy policy objectives like the further integration of the European electricity market and / or improvement of security of supply.
- *Enable access to efficient and effective system balancing and reserve capacity provision technologies in a Pan-European context*. There is a significant difference whether each single European country is exclusively responsible to be flexible enough to manage their electricity system or if countries can also "rely" on the power plant portfolios of their neighbours.
- *Harmonize legislative and regulatory frameworks in the context of grid infrastructure integration of RES-Electricity generation technologies* in the different European Member States and / or regions in order to enable better compatibility for "common" RES-Electricity projects directly affecting more than one European Member State and / or region. As an example, fundamental differences and non-harmonized approaches can be found in grid integration charging of RES-Electricity generation technologies in the different European Member States (e.g. "*deep*", "*shallow*", "*hybrid*" charging models).
- *Involve local / regional people and communities as well as several important other stakeholders and decision makers already from the beginning of the planning phase of a RES-Electricity and grid infrastructure project* and start an interactive dialog between them in order to be able to figure out several concerns, barriers and also anxieties.
- *Develop business-models where local / regional people and communities also benefit somehow if they "accept" to use "their lands" for a certain RES-Electricity and grid infrastructure project* (e.g. monetised in terms of shareholders of a particular project holding minority shares, cooperation with the local/regional tourism industry, non-monetised beneficiary models like cooperation with the education sector, etc.).

Concluding, the lessons learnt from the three (regional) scenario studies have further improved our understanding for first best solutions of grid infrastructure integration of RES-Electricity generation technologies under a variety of different constraints in the short-term and long-term.

6.2 Heating Sector

In this section, a synthesis of results of the three in-depth regional scenario studies on grid infrastructure integration of RES-Heating / RES-Gas generation technologies is conducted. Decoupled from individual regional scenario studies again, Figure 53 visualises the most important aspects and lessons learnt for the case study analyses.

Preferable Heating Strategies Depending on End-use Efficiency Ambition up to 2050			**Expected End-use Efficiency Implementation 2030-2050**	
			Low	**High**
Stand-alone	Non-grid-connected RES-Heating (e.g. stand-alone biomass in less dense & rural areas, solar thermal collectors etc.)		**o**	**+**
Network Infrastructure	**Electricity Distribution Grid**	Direct electric heating (e.g. Norway, Serbia)	**o**	**-**
		"*Innovative*" electric heating (e.g. heat pumps)	**–**	**+**
	Heat Distribution Grid	CHP-based RES-Heating (e.g. biomass / biogas in dense areas / municipalities)	**+**	**– / o**
		District heating (e.g. various fuels in dense areas / municipalities)	**+**	**– / o**
	Gas Distribution Grid	RES-Gas fed into gas distribution grid	**+**	**–**
		Natural gas & LNG fed into gas distribution grid	**+**	**–**

+ … preferable strategy **o … indifferent** **– … non-preferable strategy**

Figure 53: Preferable heating strategies depending on the end-use energy efficiency ambition in the heating sector up to 2050

Regardless of which kind of heat grid infrastructure (or stand-alone technology / technology combination) currently exists in a European region, a crucial long-term aspect in the further development of the entire portfolio of heating / hot water technologies and corresponding grid infrastructures (and combinations of different technologies) is the future ambition of the implementation of end-use energy efficiency technologies on the demand side. In this context, fundamentally different ambitions have been assumed in each of the four different storylines of the analysis. Moreover, end-use energy efficiency implementation on the demand side finally also reacts upon the economics of the different energy carriers in the local / regional heat market and the corresponding network infrastructures.

Before discussing Figure 53 in detail, some reference to the status quo is made first, describing the situation in almost all regions throughout Europe in terms of end-use energy efficiency implementation. This means that – at present – the end-use energy efficiency column on the left hand side of Figure 53 is relevant, indicating rather low awareness on (thermal) efficiency measures. In the *Red* and *Blue* storyline it has been assumed that this situation also does not change in the long-term, meaning that in the period 2030–2050 end-use energy efficiency measures are still not implemented systematically and on large-scale. Moreover, high energy demand increase in these two storylines in general is a key indicator for "*indifferent public attitude / behaviour*" (negative part of vertical axes in the storyline scheme, cf. Figure 2) in terms of energy efficiency awareness.

In an "*energy world*" like that (i.e. in the *Red* or *Blue* storyline), similar to the situation right now in almost all regions throughout Europe there exist favourable conditions (i.e. significant heat loads) for

- Heat network infrastructures like gas distribution grids (e.g. fed by natural gas, LNG and also biogas) both in dense and rural areas;
- District heating grids (e.g. heat decoupled as a by-product from combined heat and power generation technologies fuelled by natural gas, waste, biomass / biogas, others) in dense areas (cities) and also for smaller heat grids in less dense municipalities and communities;
- Direct electric heating, having tradition in some European regions (e.g. Norway). Although direct electric heating was implemented also in other European regions in the past (e.g. Austria), this technology type is increasingly phased-out (high variable cost, controversial from the environmental point-of-view in case of non-renewable electricity generation). Innovative heat technologies like heat pumps are no option in energy systems characterised by poor thermal efficiency standards;
- Stand-alone heat technology options (e.g. old biomass (split logs), coal), being used simply due to necessity. Innovative technologies like biomass (chips) and / or pellets in combination with solar thermal collectors are no option in energy systems characterised by poor thermal efficiency standards.

However, in terms of end-use energy efficiency standards on the demand side, "*energy worlds*" in a long-term period 2030–2050 shall be much more ambitious than those described above. Even more, the end-use energy efficiency standard column on the right hand side of Figure 53 (describing the settings of the *Yellow* and *Green* storyline) is rather a "*must*" than a "*can*". Having in mind the merit order curve of CO_2 abatement cost, energy efficiency measures are characterised by negative CO_2 abatement cost; meaning that they shall get highest priority for implementation as soon as possible. In order to mitigate at least parts of the CO_2 emission problem in the heating sector it is expected that in a long-term perspective a "*real world*" will be described by the column on the right hand side of Figure 53. In detail, in a world of significantly decreasing heat loads the situation is as follows:

- In general, several grid-connected heating technologies and technology combinations are increasingly confronted with significant troubles; except electricity grids supplying innovative technologies like heat pumps (direct electric heating is supposed to be the least elegant technology solution in a sustainable energy world). High energy efficiency standards are, furthermore, also favouring innovative stand-alone solutions like biomass (chips) and / or pellets in combination with solar thermal collectors in less dense and rural areas.
- In particular, conditions for gas distribution grids (supplying the residential and tertiary sector) may become increasingly existence-threatening in many regions. They are simply not needed any more in the long-term; at least not in the *Green* and *Yellow* storyline (see e.g. corresponding analyses for Austria, Spain, etc.). So already at present a further extension of gas distribution grids may have the "*smell of a myopic energy policy*" in many cases. At this point it is important to note, however, that

corresponding gas infrastructures “*fuelling*” the industrial and power generation sector are not meant here!

- District heating, finally, an ambiguous future is bestowed. On the one hand, “*competitors*” like energy efficiency, solar thermal collectors and others contest market shares of heat loads in areas with medium / average density but, on the other hand, district heating is supposed to be still the first best solution in dense areas like cities and bigger municipalities.

7 Conclusions

The analyses conducted in this thesis have impressively demonstrated the complexity and diversity of dimensions having to be considered when trying to integrate large amounts of RES-Electricity, RES-Heating and RES-Gas generation technologies into the corresponding grid infrastructures in different European countries and regions. The case study processes themselves, the interactions with the local / regional actors in this context during the case study analyses (providing both insights into the regional barriers / obstacles as well as empirical data for the analyses) as well as the outcomes of the different regional scenario studies throughout Europe have significantly contributed to further improve our common understanding how best to "tackle" the challenges inherently linked to the continuous transformation process towards more sustainable energy systems in Europe.

One of the most novel aspects of the regional energy systems' analyses has been the quantification of both RES-Electricity, RES-Heating and RES-Gas generation technology penetration and corresponding grid infrastructures needs and costs in a long-term time horizon up to 2050, on the one hand, and also the identification of interdependences and partly competing drivers between different renewable resources and corresponding grid infrastructures qualified to serve different energy services, on the other hand.

It is important to note, however, that it has not been the intention of the regional scenario studies to draw a full picture of solutions and / or best-practise examples of grid infrastructure related aspects of RES-Electricity, RES-Heating and RES-Gas generation technology integration under a variety of different constraints and settings, being of geographical, structural, technical, economical, institutional, and political nature. It rather has been an attempt to further structure the discussion on grid infrastructure related challenges and problems having to be mitigated and overcome, respectively, to enable the absorption of large amounts of RES-Electricity, RES-Heating and RES-Gas generation on several time scales, short-term and long-term.

Especially the emphasis on the long-term perspective up to 2050 in the analyses in general, regional and trans-national, shall demonstrate that there exist significant interdependencies between short-term energy policy decisions and long-term options to integrate large amounts of RES-Electricity, RES-Heating and RES-Gas generation technologies into the different network infrastructures. A simple explanation for these interdependencies is as follows: once capital-intensive network infrastructures are implemented, the corresponding investments are definitely sunk and, subsequently, the implemented network infrastructures inherently predetermine the pattern of a particular regional energy system not only for years but for decades. And this heavily affects any kind of renewable energy policy decisions in the future.

This is exactly the aspect having to be taken into account also in the short- / medium term policy making, because this will finally define in which "*energy world*" we will "*awake*" in 2030, the starting point of the case study analyses in the different storylines in this thesis.

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Appendix

A.1 Biomass Price Development up to 2050

Figure A.1 below shows the graphical representation of the biomass price development in the four different storylines up to 2050.

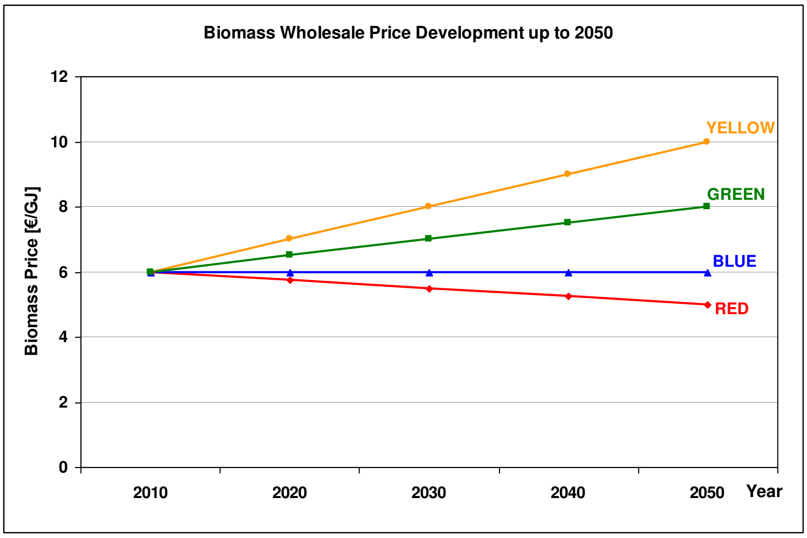
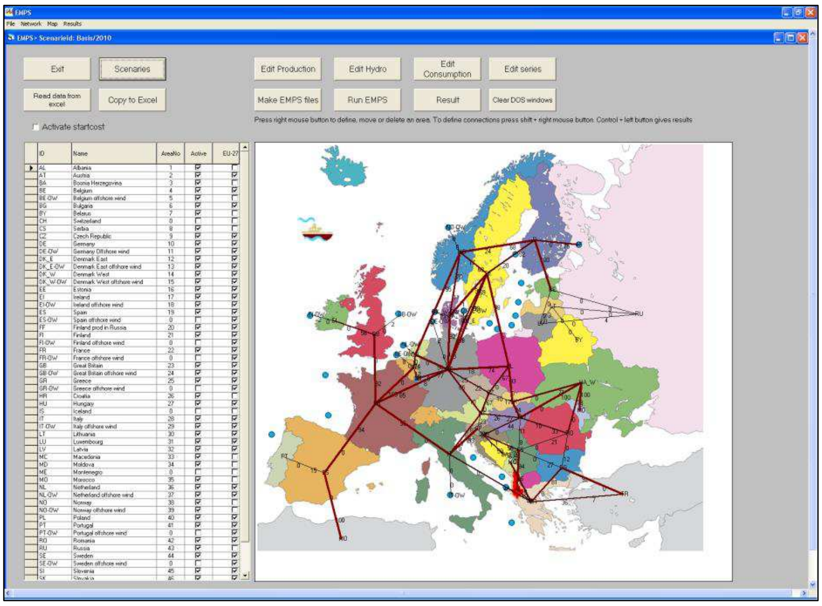


Figure A.1: Expected development of the biomass wholesale prices up to 2050 in the four different storylines (Source: see text section 2.2.4)

A.2 EMPS Electricity Market Model

In the EMPS model each European country is considered as a single node (characterized by an endogenously determined internal supply and demand balance) with distinct import and export transmission capacities to the neighbouring countries, see a screenshot of the model in Figure A.2.



☐ Activate startcost

Press right mouse button to define, move or delete an area. To define connections press shift + right mouse button. Control + left button gives results

ID	Name	AreaNo	Active	EU-27
AL	Albania	1	☑	☐
AT	Austria	2	☑	☑
BA	Bosnia Herzegovina	3	☑	☐
BE	Belgium	4	☑	☑
BE-OW	Belgium offshore wind	5	☑	☐
BG	Bulgaria	6	☑	☑
BY	Belarus	7	☑	☐
CH	Switzerland	0	☐	☐
CS	Serbia	8	☑	☐
CZ	Czech Republic	9	☑	☑
DE	Germany	10	☑	☑
DE-OW	Germany Offshore wind	11	☑	☑
DK_E	Denmark East	12	☑	☑
DK_E-OW	Denmark East offshore wind	13	☑	☑
DK_W	Denmark West	14	☑	☑
DK_W-OW	Denmark West offshore wind	15	☑	☑
EE	Estonia	16	☑	☑
EI	Ireland	17	☑	☑
EI-OW	Ireland offshore wind	18	☑	☑
ES	Spain	19	☑	☑
ES-OW	Spain offshore wind	0	☐	☑
FF	Finland prod in Russia	20	☑	☑
FI	Finland	21	☑	☑
FI-OW	Finland offshore wind	0	☐	☑
FR	France	22	☑	☑
FR-OW	France offshore wind	0	☐	☑
GB	Great Britain	23	☑	☑
GB-OW	Great Britain offshore wind	24	☑	☑
GR	Greece	25	☑	☑
GR-OW	Greece offshore wind	0	☐	☑
HR	Croatia	26	☑	☐
HU	Hungary	27	☑	☑
IS	Iceland	0	☐	☐
IT	Italy	28	☑	☑
IT-OW	Italy offshore wind	29	☑	☑
LT	Lithuania	30	☑	☑
LU	Luxembourg	31	☑	☑
LV	Latvia	32	☑	☑
MC	Macedonia	33	☑	☐
MD	Moldova	34	☑	☐
ME	Montenegro	0	☐	☐
MO	Morocco	35	☑	☐
NL	Netherland	36	☑	☑
NL-OW	Netherland offshore wind	37	☑	☑
NO	Norway	38	☑	☐
NO-OW	Norway offshore wind	39	☑	☐
PL	Poland	40	☑	☑
PT	Portugal	41	☑	☑
PT-OW	Portugal offshore wind	0	☐	☑
RO	Romania	42	☑	☑
RU	Russia	43	☑	☐
SE	Sweden	44	☑	☑
SE-OW	Sweden offshore wind	0	☐	☑
SI	Slovenia	45	☑	☑
SK	Slovakia	46	☑	☑

Figure A.2: EMPS electricity market model

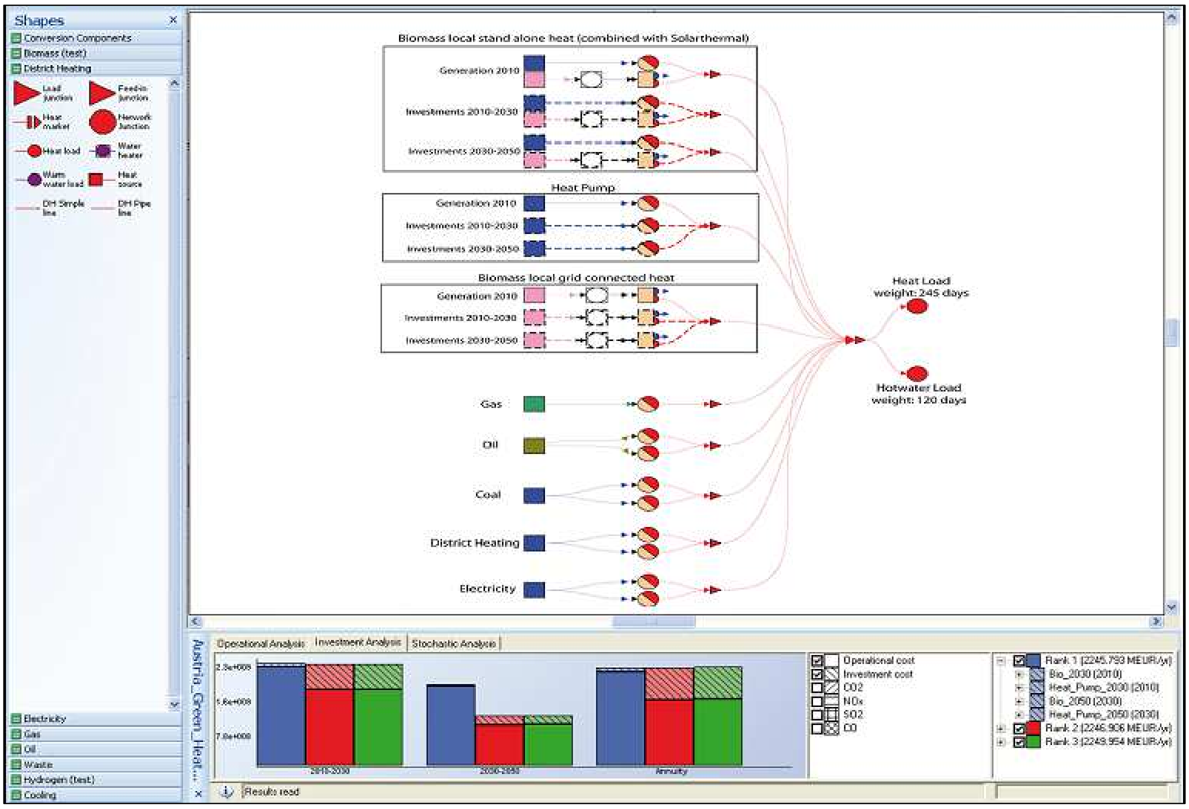
A.3 (P)HES Potential in Europe up to 2050

The following Table A.1 shows the input data for Figure 13 (section 3.1.3), i.e. European (P)HES potential data until the year 2050.

Table A.1: (P)HES Potential in Europe until the year 2050 (Source: see text in section 3.1.3)

(P)HES	[MW]	[kW/km^2]
Albania	0	0.00
Austria	12800	152.60
Belgium	1300	42.58
Bosnia-Herzeg.	1520	29.69
Bulgaria	2790	25.14
Croatia	1900	33.60
Czech Rep.	1900	24.09
Denmark	0	0.00
Estonia	500	11.06
Finland	0	0.00
France	19500	35.65
Germany	12187	34.13
Greece	4809	36.44
Hungary	600	6.45
Ireland	1322	18.84
Italy	15600	51.77
Latvia	0	0.00
Lithuania	1600	24.50
Luxembourg	1300	502.71
Macedonia	1370	53.28
Montenegro	900	65.16
Netherlands	0	0.00
Norway	30000	77.88
Poland	1950	6.24
Portugal	5700	61.81
Romania	4550	19.09
Serbia	1300	16.78
Slovakia	1330	27.12
Slovenia	600	29.60
Spain	20200	40.03
Sweden	16200	35.98
Switzerland	14400	348.79
UK	4088	16.90
TOTAL	**182216**	

A.4 eTransport Economic Trade-off Analyses of RES-Heating Technologies in Austria



☑ Operational cost
☑ Investment cost
☐ CO2
☐ NOx
☐ SO2
☐ CO

☑ Rank 1 (2245.793 MEUR/yr)
- Bio_2030 (2010)
- Heat_Pump_2030 (2010)
- Bio_2050 (2030)
- Heat_Pump_2050 (2030)

☑ Rank 2 (2246.906 MEUR/yr)
☑ Rank 3 (2249.954 MEUR/yr)

Figure A.3: *eTransport* model: Economic trade-off analyses of RES-Heating technologies meeting heat-loads in Austria in the four different storylines

A.5 RES-Electricity Deployment in Austria in the four different Storylines 2010–2050

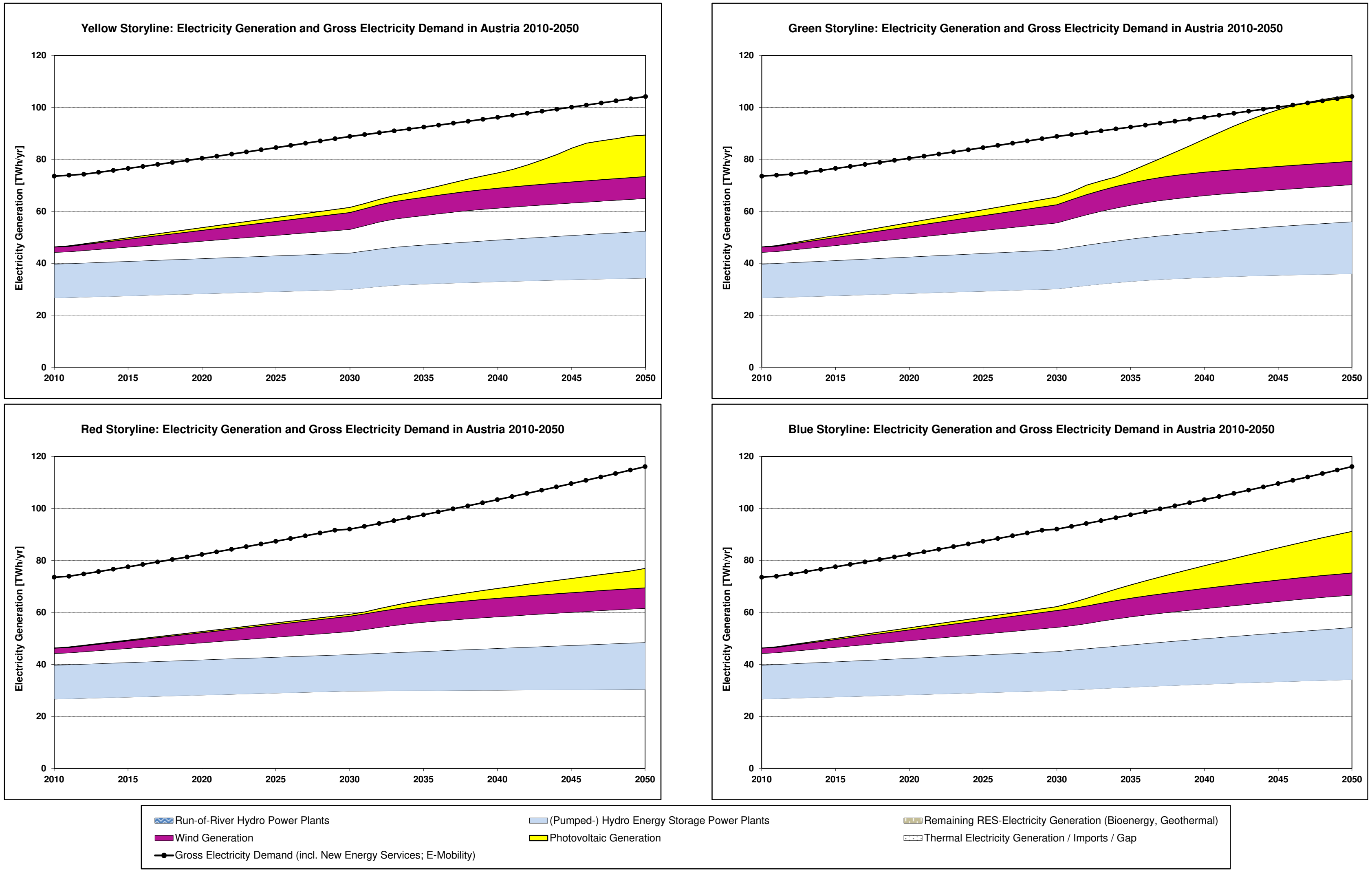


Figure A.4: Electricity generation portfolio and gross electricity demand in the four different storylines in Austria from 2010 to 2050 (Source: own calculations)

A.6 RES-Electricity Deployment in Serbia in the four different Storylines 2010–2050

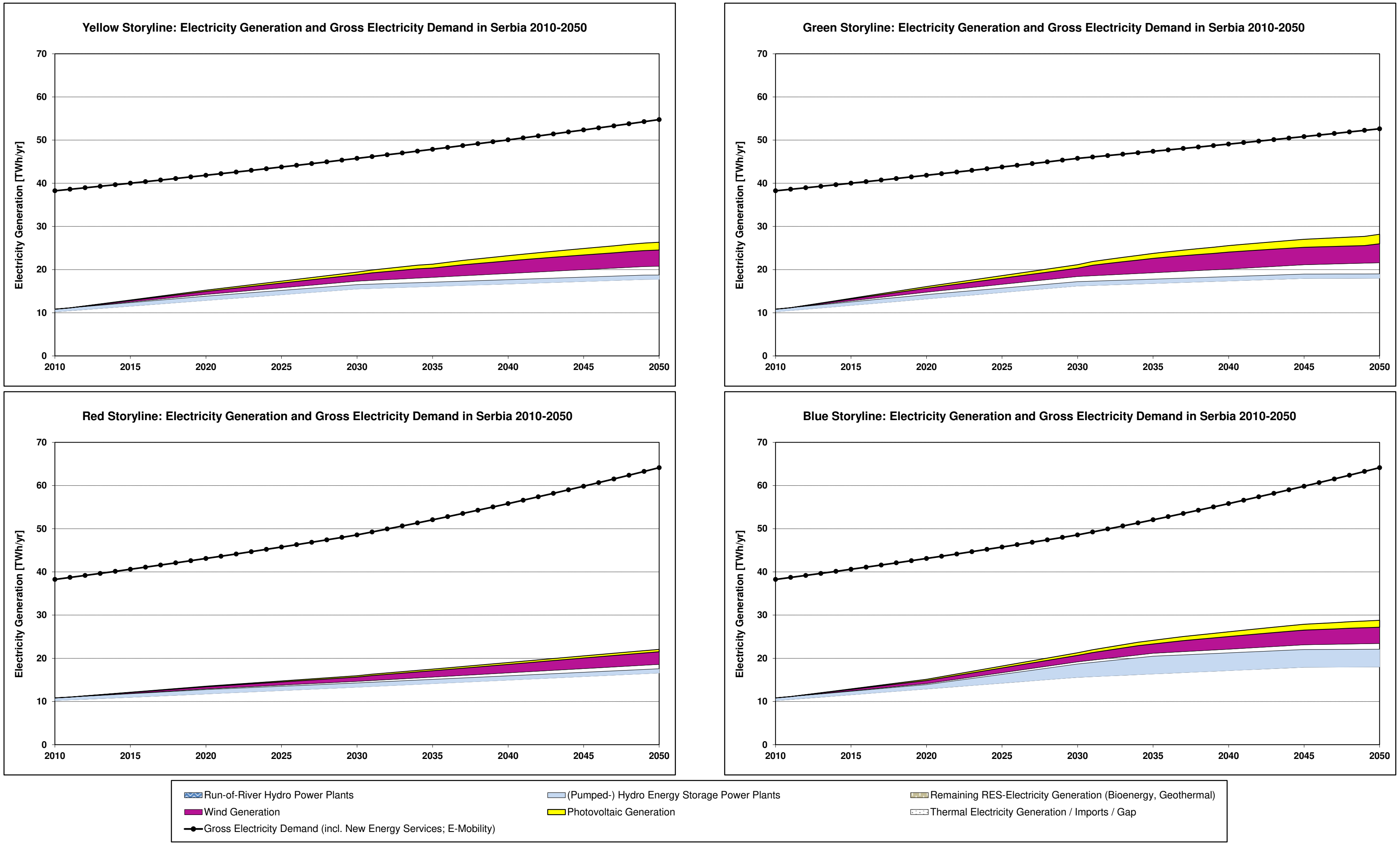


Figure A.5: Electricity generation portfolio and gross electricity demand in the four different storylines in Serbia from 2010 to 2050 (Source: own calculations)

A.7 Age Structure of the Thermal Power Plant-Portfolio

Figure A.6 and Figure A.7 show the status quo of the age structure of the thermal power plant portfolio in the Western Balkan region and Iberian Peninsula respectively.

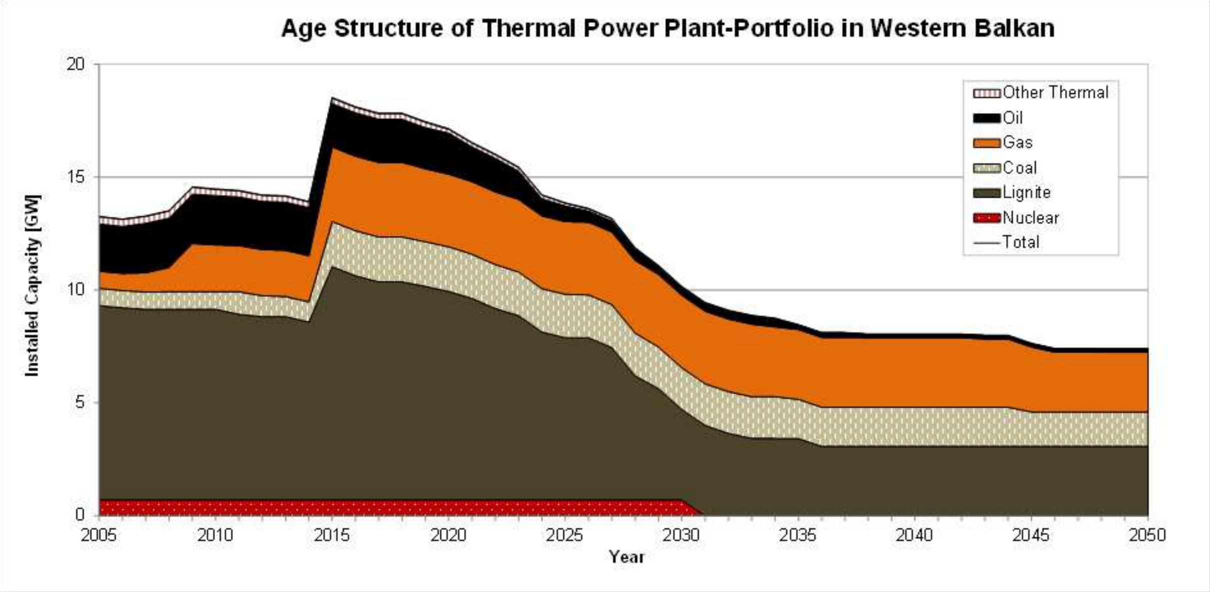


Figure A.6: Age structure of the thermal power plant-portfolio in the Western Balkan region (Data source: PLATTS, 2010)

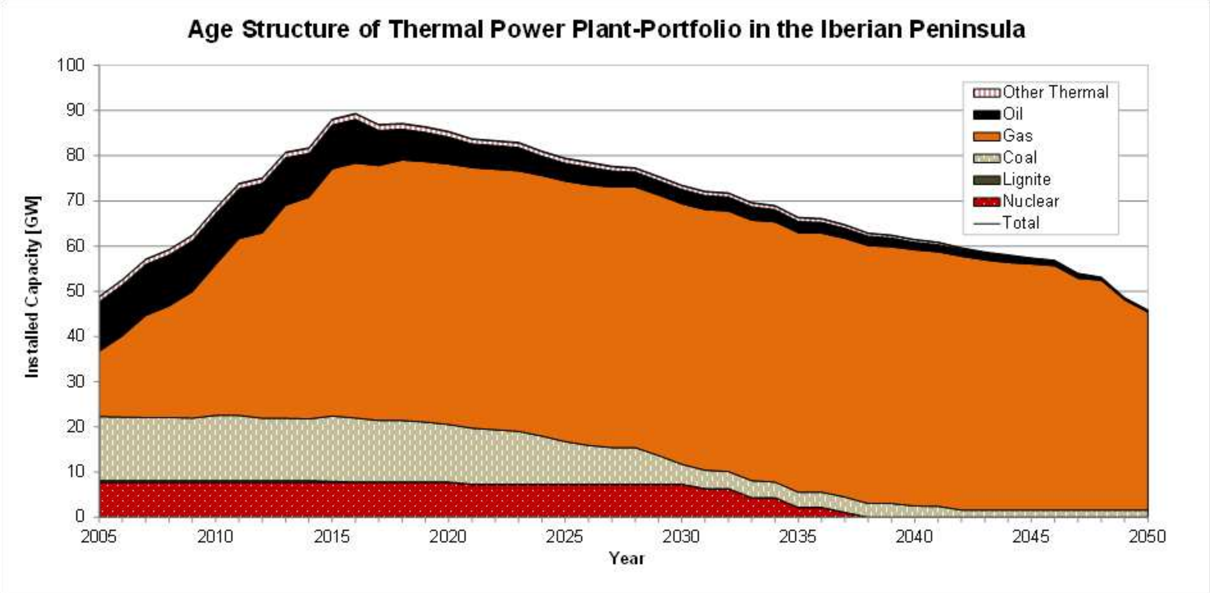


Figure A.7: Age structure of the thermal power plant-portfolio in the Iberian Peninsula (Data source: PLATTS, 2010)

A.8 Contribution of Transmission Grid Expansion within the EEMRs

The result tables below give detailed information about the contribution of transmission grid expansion for mitigation of variable RES-Electricity generation (e.g. wind) within the EEMRs and management of extreme weather events (i.e. input for Figure 47 in section 4.5).

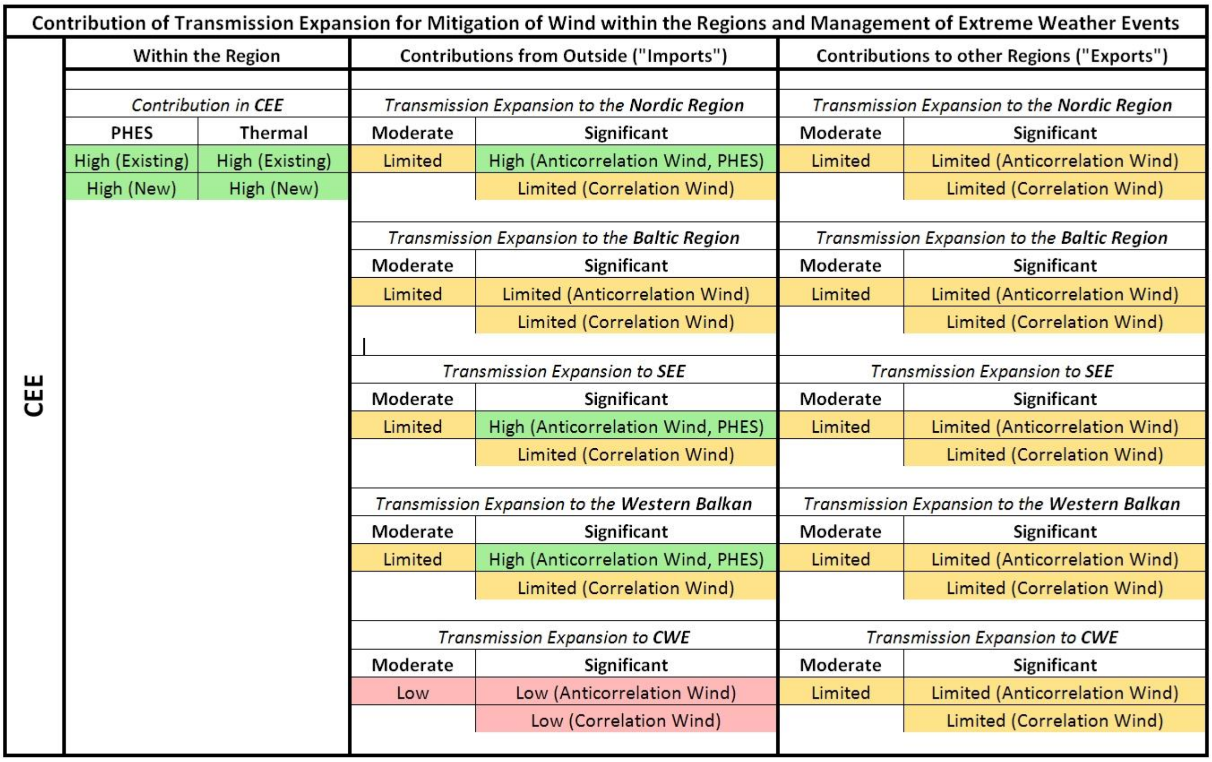
Table A.2: Contribution of transmission grid expansion for mitigation of variable RES-Electricity generation (e.g. wind) within the Western Balkan region

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")	
	*Contribution in **SEE***		*Transmission Expansion to **CWE***		*Transmission Expansion to **CWE***	
	PHES	Thermal	Moderate	Significant	Moderate	Significant
Western Balkan	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)

Table A.3: Contribution of transmission grid expansion for mitigation of variable RES-Electricity generation (e.g. wind) within the Nordic region and the Iberian Peninsula

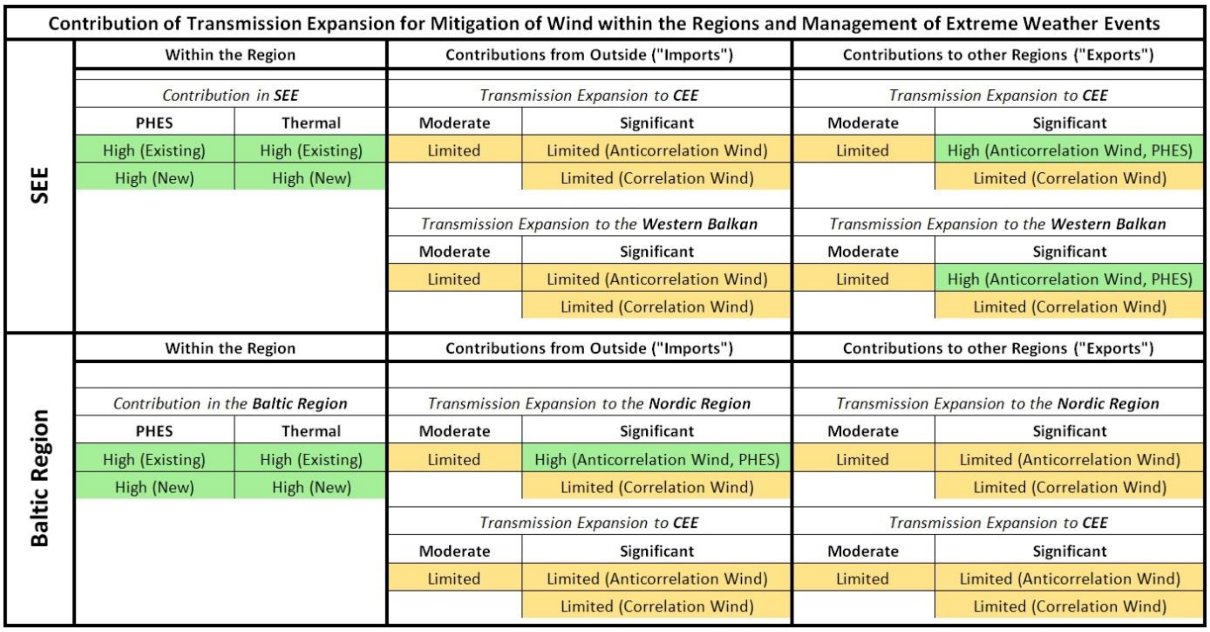
Contribution of Transmission Expansion for Mitigation of Wind within the Regions and Management of Extreme Weather Events						
	Within the Region		Contributions from Outside ("Imports")		Contributions to other Regions ("Exports")	
	*Contribution in the **Nordic Region***		*Transmission Expansion to **UK & Ireland***		*Transmission Expansion to **UK & Ireland***	
	PHES	Thermal	Moderate	Significant	Moderate	Significant
Nordic Region	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)

Table A.4: Contribution of transmission grid expansion for mitigation of variable RES-Electricity generation (e.g. wind) within the CEE region



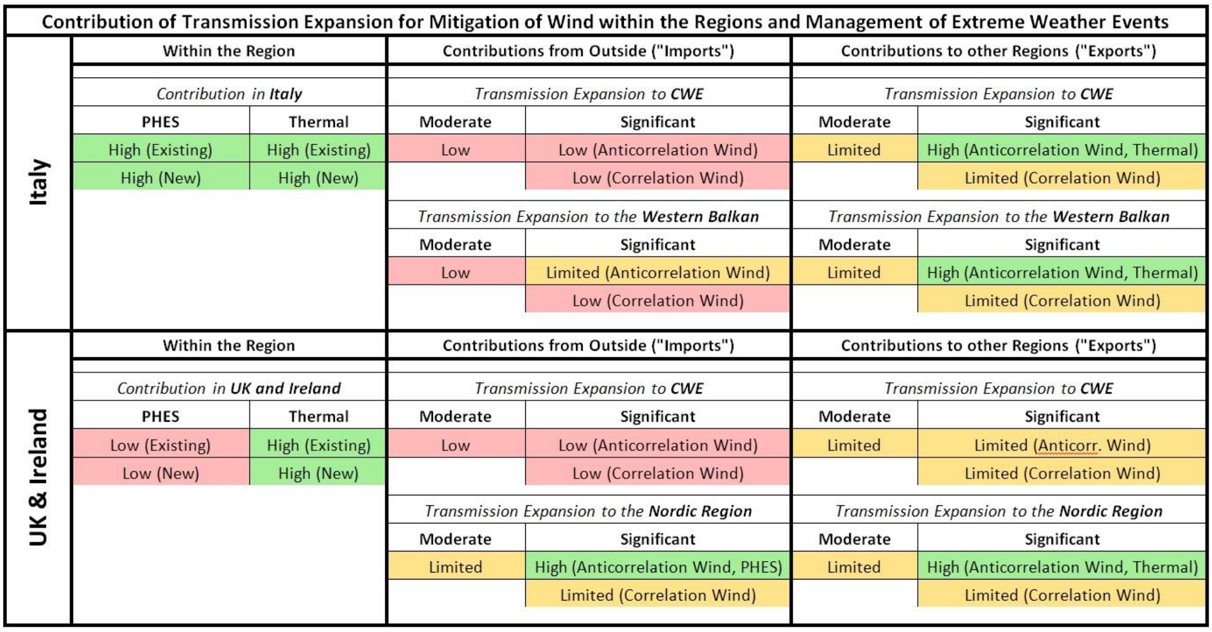
Contribution of Transmission Expansion for Mitigation of Wind within the Regions and Management of Extreme Weather Events						
CEE	**Within the Region**		**Contributions from Outside ("Imports")**		**Contributions to other Regions ("Exports")**	
	Contribution in ***CEE***		*Transmission Expansion to 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)

Table A.5: Contribution of transmission grid expansion for mitigation of variable RES-Electricity generation (e.g. wind) within the SEE and the Baltic region



Contribution of Transmission Expansion for Mitigation of Wind within the Regions and Management of Extreme Weather Events						
SEE	**Within the Region**		**Contributions from Outside ("Imports")**		**Contributions to other Regions ("Exports")**	
	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)

Table A.6: Contribution of transmission grid expansion for mitigation of variable RES-Electricity generation (e.g. wind) within Italy and the UK & Ireland region



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)

A.9 End-Use Energy Demand in the Residential Heating Sector in Austria from 2010 to 2050 in the different Storylines

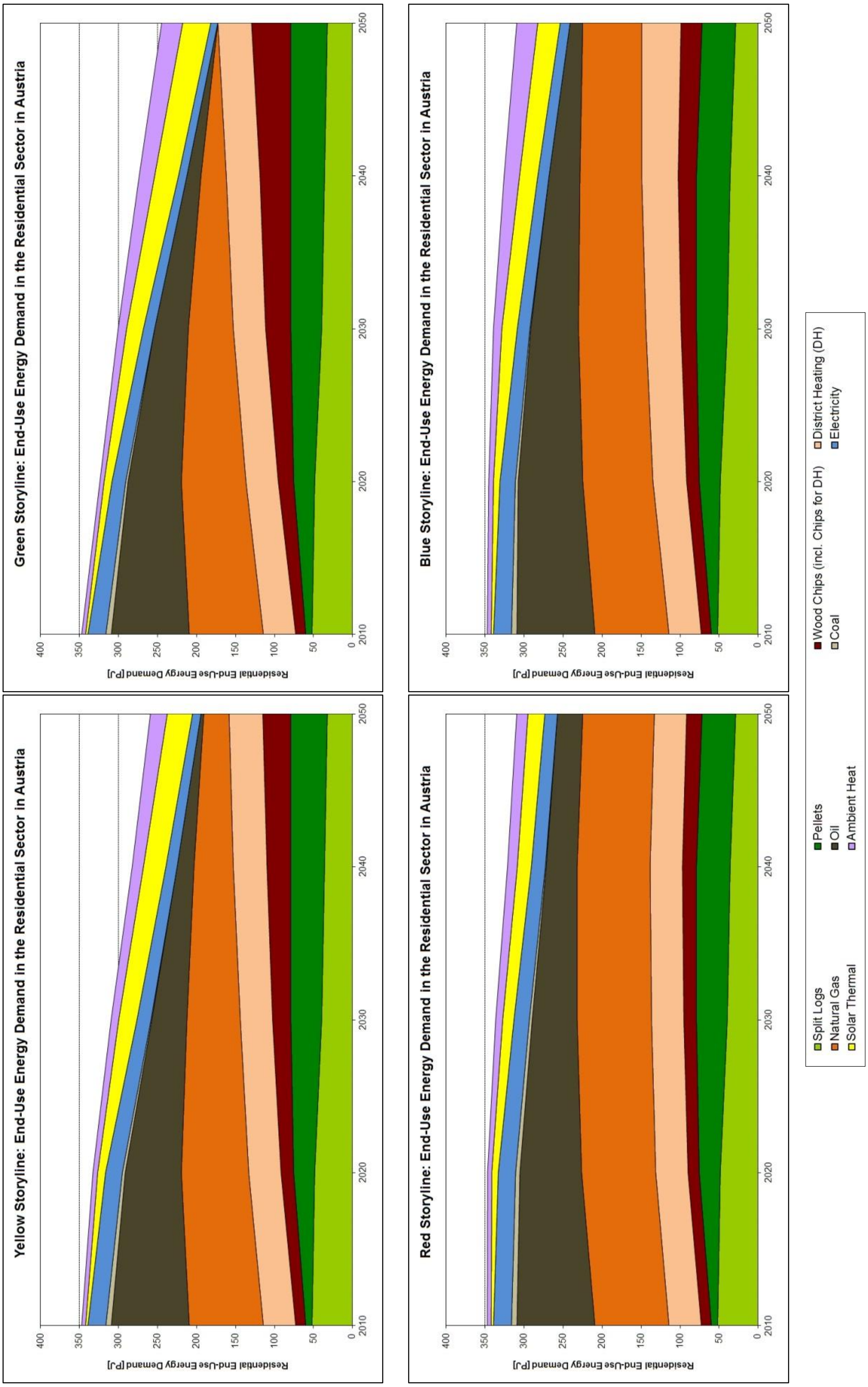


Figure A.8: End-use energy demand in the residential heating sector in Austria from 2010 to 2050 in the different storylines (Source: see section 5.1.2)

A.10 GAMS-Code of the Linear Optimization Algorithm

```

* Listing of used indices
set
t /1*8760/
;
alias
(t,t1)
;

* Listing and pre-configuration of used parameters
parameters
PmaxTurb Maximum Power in turbine-mode           /35/
PmaxPump Maximum Power in pump-mode              /30/
PminTurb Minimum Power in turbine-mode           /0.1/
PminPump Minimum power in pump-mode              /0.1/
Emax     Maximum energy content of reservoirs    /4000/
E_end    Energy content of reservoirs at end     /2000/
ETA      Efficiency                              /0.9/


anzT     Number of time steps
RLmax    Maximum value of residual load
RLmin    Minimum value of residual load

RL(t)    Residual load in time step t


* Data import from Excel using GDX utilities

$onecho > commands.txt
par  = RL      rng=Data!A3:B8762     RDim=1

$offecho
$call GDXXRW Data+Results.xlsx @commands.txt

* Import residual load data from GDX
$GDXIN Data+Results.gdx
$LOAD RL
$GDXIN

;

* Assignment of parameters anzT, RLmin and RLmax
anzT = card(t);
display anzT;

RLmin = smin(t, RL(t));
display RLmin;

RLmax = smax (t, RL(t));
display RLmax;

variable
v_RLopt

positive variable
v_Pturb(t)               Power of turbine in time step t
v_Ppump(t)               Power of pump in time step t
v_Energy(t)              Energy content of reservoirs in time step t

;

* Listing of equations and constraints
equations
e_RLopt
e_Storage(t)             Storage balance in time step t
e_endEnergy              Energy content in time step T8760
e_maxEnergy(t)           Maximum energy content in time step t
e_Tmax(t)                Maximum turbine power in time step t
e_Pmax(t)                Maximum pump power in time step t
e_PmaxRL(t)              Maximum pump power under consideration of RL in time step t
```

```
e_TmaxRL(t)              Maximum turbine power under consideration of RL in time step t
e_PmaxRLpos(t)           Maximum pump power at positive RL in time step t
e_PmaxRLneg(t)           Maximum pump power at negative RL in time step t
e_PmaxPRL(t)             Maximum pump power in case of RL+PmaxPump<0 in time step t
;

* Assignment of equations and constraints
e_RLopt ..                 v_RLopt  =e=  sum(t, RL(t)*(v_Pturb(t)-v_Ppump(t))) ;

e_Storage(t) ..            v_Energy(t) =e=  v_Energy(t--1)+v_Ppump(t)*ETA-v_Pturb(t)/ETA ;

e_endEnergy ..         v_Energy('8760')  =e=  E_end ;
e_maxEnergy(t) ..      v_Energy(t)  =l=  Emax ;
e_Tmax(t) ..           v_Pturb(t)  =l=  PmaxTurb ;
e_TmaxRL(t) ..         RL(t)$(RL(t)>0)-v_Pturb(t) =g=  0 ;
e_Pmax(t) ..           v_Ppump(t) =l=  PmaxPump ;
e_PmaxRL(t) ..         RL(t)+v_Ppump(t)-v_Pturb(t) =l=  RLmax-PmaxTurb ;
e_PmaxRLneg(t) ..      v_Ppump(t)$((-RL(t))>=PmaxPump) =e=  PmaxPump$((-RL(t))>=PmaxPump) ;
e_PmaxRLpos(t) ..      v_Ppump(t)$(RL(t)>=0) =l=  (RL(t))$(RL(t)>=0) ;
e_PmaxPRL(t) ..        RL(t)+v_Ppump(t)-v_Pturb(t) =g=  RLmin+PmaxPump$(RLmin+PmaxPump<0) ;


model DISS_01 /e_RLopt,e_Storage,e_endEnergy,e_maxEnergy,
e_Tmax,e_TmaxRL,e_Pmax,e_PmaxRL,e_PmaxRLneg,e_PmaxPRL/;

option LP = OSICPLEX;

solve DISS_01 using LP maximising v_RLopt;

display v_Energy.l,v_Pturb.l,v_Ppump.l;

*Export data from GDX
execute_unload "Data+Results.gdx"
v_Ppump.l
v_Pturb.l
v_Energy.l
v_RLopt

execute 'gdxxrw.exe Data+Results.gdx SQ = N var=v_Ppump.l  rng=Results!C2:D8761 RDim=1'
execute 'gdxxrw.exe Data+Results.gdx SQ = N var=v_Pturb.l  rng=Results!E2:F8761 RDim=1'
execute 'gdxxrw.exe Data+Results.gdx SQ = N var=v_Energy.l rng=Results!G2:H8761 RDim=1'

```

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