Final Report

RESDEGREE

Towards an energy system in Europe based on renewables – Model based analysis of Greece and Germany by coupling a European wide demand and supply model (PRIMES) with a regional and temporal high resolution bottom-up investment and unit-commitment model (RESlion)

Final Report
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1. Introduction

Penetration of renewable energy sources (RES) is a key element of the EU energy strategy. The EU has been exploring strategic scenarios of decarbonizing the economy (Energy Roadmap [1]), setting an objective of reducing the GHG emissions by 80% in 2050 compared to 1990 levels. All of these scenarios emphasize on reaching very high shares of RES in the national power generation systems. The decarbonization goals that the EU has set for itself are gradually materializing into policies with specific targets for the short to medium term, with the well-known 20-20-20 package setting the 2020 milestone (20% CO_2 emission reduction and 20% energy efficiency compared to 1990, 20% share of RES in primary energy consumption). Since October 2014, the EU adopted targets that go beyond the 20-20-20 package, with a horizon to 2030[1]. The adopted strategy includes significantly high development of RES within a decarbonization pathway; in particular it includes a GHG emissions reduction reaching 40% by 2030 compared to 1990 levels accompanied by a 27% share of RES in energy consumption.

As renewables, and in particular variable RES (namely wind and solar PV, referred to also as intermittent RES), are increasing their presence in the national power systems there emerge several issues related to their expansion, use and integration in the system stemming from the intermittency of their generation patterns. These issues regard the reliability of the system and the efficient functioning of the market (we will refer to them in more detail in following paragraphs). What is key in tackling those issues is the effective use of resources. Within national and sub-national systems it is naturally the case that a non-optimal availability of resources is observed. When looking at several regions, significant complementarities appear between them that are calling for the sharing of system resources. This sharing however has as prerequisites the enhancement of interconnections and the coupling of the markets.

The objective of the RESDEGREE project is to use detailed mathematical modelling techniques in order to study possible benefits from energy system integration in a regional EU context of future German and Greek power sector developments, aiming at a high contribution of renewable power sources in both countries. In particular, this project will conduct an energy system analysis to study in detail the electricity systems of Greece and Germany in the context of high penetration of intermittent RES; in parallel it will explore the possibility of development of interconnecting paths between the two countries in order to maximize the capacity and use of intermittent RES in both countries.

The RESDEGREE project is funded by the General Secretariat of Research and Development of the Greek Ministry of Culture, Education and Religious Affairs (Greece) and the Federal Ministry of Education and Research BMBF (Germany). This report is the final report of the project, analyzing the results of the project. Results of the project have been published as papers and presented at the 12th International Conference on the European Energy Market (EEM15) ([1] and [2]). Moreover, results have been presented at a workshop organised in particular for this project in Berlin, on April 2015.

The potential of RES in the EU is quite significant. This potential differs by source between the member states (MS), however it is most significant for variable RES. Relevant studies ([4]-[5]) indicate that the potential for dispatchable types of RES, such as hydro and biomass, is relatively limited. Therefore, moving to a high RES context implies a move to a high variable RES context, which entails significant challenges for system reliability. To understand these challenges we should look at the implications in the "net load curve" from introducing variable RES to the power system. The net load curve is defined as demanded load minus generation by variable RES; therefore it corresponds to the demand that needs to be met by dispatchable system resources. Due to the variability of renewable resources, the net load curve of systems with high RES penetration is characterized by significant and stochastic fluctuation on both daily and sub-hourly timescales. Dealing

[1] https://ec.europa.eu/energy/en/topics/energy-strategy/2030-energy-strategy

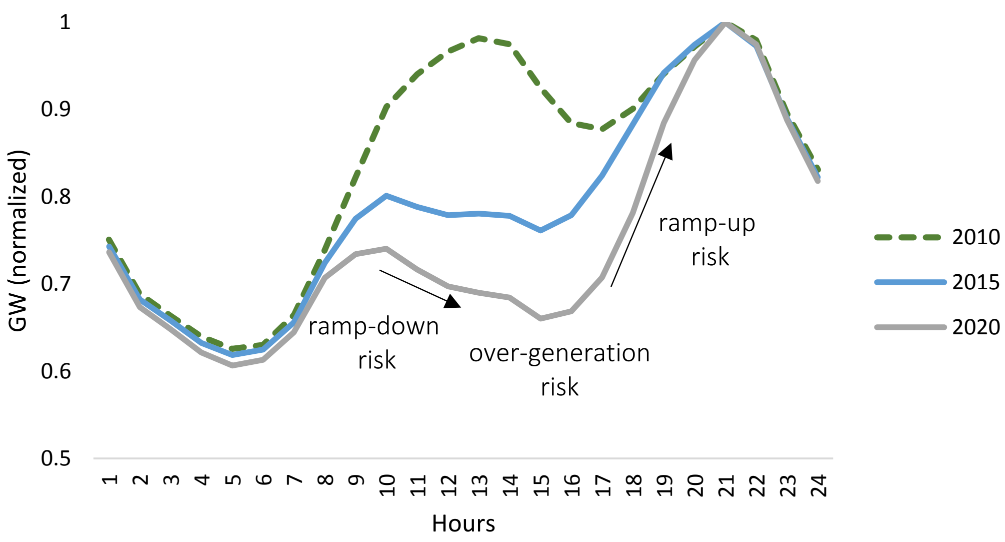
with the variability of load and the stochastic nature of changes calls upon handling dispatchable resources that are sufficiently flexible. For thermal plants this implies strong cycling operation alternating between minimum stable generation power levels, frequent starts/stops and fast ramping. Not all plant technologies can cope with such requirements. Clearly hydro power with reservoir and storage systems can have ideal features from a flexibility perspective, but their potential is either limited or very costly. On the other hand, maintaining large amounts of thermal capacities with high flexibility features is challenging from a market perspective (studies that support this argument are [6] and [7]). Reliability in a context of high RES is like a public good implying that it is difficult that requirements are fully met on a pure private basis as free riding on reliability is common among competitors.

The various variable RES types have different implications for the variability features of the net load curve. Wind generation demonstrates significant variability on an hourly or even on a minute-by-minute basis. This variability is naturally more pronounced when looking at a single wind farm than when looking at all the wind farms in a country or in a wider region; studies (such as [8]) show significant wind penetration that is accompanied by geographical dispersion results in wind generation patterns that are more uniform through the day. Daily patterns are difficult to distinguish except when looking at a more aggregate level, for example on a seasonal basis. Overall, wind penetration has far higher impacts on a sub-hourly timescale where randomness is significant.

Solar PV on the other hand, has naturally a systematic daily pattern following the sunlight. Penetration of solar capacity sharply reduces the net load curve in the mid-day hours and it introduces considerable ramp-up requirements during sunset when demand is also rising. The resulting effect on the net load curve is an increasingly deep valley at the hours of solar generation which in the literature is said to resemble a "duck" shape. Fig. 1 provides an example of this effect based on projections of RES penetration in Greece. We see in Fig. 1 that the "duck" shape entails three types of risk for the power system; a) sharp ramp-down requirements at the hours that solar PV generation emerges, b) sharp ramp-up requirements as solar PV generation stops, and c) risk of over-generation at times when solar PV generation is at its peak while demand is moderate, during which dispatchable capacities would need to be required to operate at their technical minimum.

Due to the differences in the patterns of the variable RES it is possible to identify complementarities

Figure 1: Typical net load curve for Greece in 2010 and projection to 2020 (source: E3MLab)



between countries which if exploited can mitigate the flexibility challenges posed for the energy systems and increase the amount of exploitable RES. As example, Germany and Greece have a large potential of renewables; off-shore and on-shore wind as well as solar PV in Germany, solar energy and on-shore wind in Greece. Complementarity of resource availability can be greatly beneficial to the system reliability and economics of both countries, however, the interconnection routes between the two countries are weak and do not allow to exploit benefits from coordinating RES policies and sharing energy system resources. High RES European scenarios require significant enhancement of the interconnection grids not only to access remotely located RES but also to share flexibility and balancing resources. Such a sharing is obstructed by insufficiency of interconnections along the various routes connecting Greece and Germany.

The described context is the basis for the analysis conducted for the RESDEGREE project and presented in this report. The analysis focuses on exploring possible synergies of the German and Greek power sectors from high development of renewable power in the European electricity system. This means an optimal deployment of respective resources and the possible extension of interconnection routes. For this purpose, the analysis investigates European electricity scenarios with a focus on Germany and Greece by using a specific option to extend interconnections between both countries. Scenarios explore whether the enhanced European and national systems could capture benefits from energy system and resource complementarities.

The objectives of the analysis call for a detailed look at the national energy systems while also considering how the national systems are embedded within the pan-European energy grid. For this purpose the analysis applies two different energy system models; the PRIMES pan-European energy system model of ICCS/E3MLab and the RESlion high resolution investment and unit-commitment model of Fraunhofer ISE. The coupling of the two models has been provided with a tool that combines the national and the European perspective of the future electricity systems. In particular, PRIMES covers the aspect of analysing the pan-European energy system, while RESlion covers the regional and temporal high resolution energy system optimization within a given country.

2. Modelling set-up

This project's scope is to quantify in detail through modelling the technical and economic parameters as well as the impacts of an enhanced German-Greek power system integration in the context of very high penetration of renewables in power generation. For this purpose, the two project teams are pursuing the coupling of two models; PRIMES of E3MLab/ICCS, a hybrid top-down, bottom-up demand and supply model of the European energy system, and RESlion of Fraunhofer ISE, a regional and temporal high resolution bottom-up investment and unit-commitment model for Germany and Greece.

The coupling of PRIMES and RESlion has resulted in a tool that meets all requirements for assessing the pan-European energy system transformation to an energy system based on renewable energy. In particular, the PRIMES model covers the aspect of analysing the pan-European energy system on a country level including power flow allocation of interconnecting capacities. With its five year time period it has a high level of aggregation of the investment and unit-commitment problem for the power sector. It is integrated into a system wide model coupled with demand and fuel supply systems as well as the interconnections of the power sector covering the individual member-states of the EU-28 and its neighbour countries in Europe. It is dynamic over time and capacity expansion is determined endogenously together with demand and prices. It can therefore provide an overview of the European energy system, determining demand prices etc.

On the other hand, the detailed power sector model RESlion covers the regional and temporal high resolution energy system optimization within a given country. It performs hourly unit commitment, handling renewables system integration in a detailed planning and operating modeling and capturing technical constraints of system operation including ancillary services. It can provide regional disaggregation within countries regarding power plant investments and dispatch, storage investment and dispatch, renewable energy distribution and transmission capacity planning of the high voltage grid.

The two models are also different in regard to their formulation which considerably affects investment decision and selection of technologies. In particular, the PRIMES model incorporates non-linear formulations on many aspects of the decision making, including non-linear cost-quantity curves related to the potential of renewable resources, fuel supply, site limitations for development of new plants, etc. Such formulations are not included in the RESlion model which is a linear model.

Both models simulate the regional interconnected system within the Internal Energy Market (IEM) context, including power flow allocation of interconnecting capacities and their enhancement by undertaking extensions and new investment. In RESlion, grid extension is considered specifically in each country while PRIMES ensures the modelling of the rest of the regional countries participating in the integration, thus allowing to model with consistency the grid extensions in the two countries within the IEM.

In the following each model is presented separately. Additionally a description of their coupling is given to provide information regarding the interfaces and exchange between the models.

2.1. The PRIMES model

In this section we will provide a description of the key characteristics and functions of the PRIMES model that are most relevant to the analysis conducted for RESDEGREE. For a more detailed description of the PRIMES model, the reader is referred to [9].

General description

PRIMES is a modular hybrid market equilibrium model which incorporates both engineering and economics principles to represent the energy decisions of agents, with a medium to long term horizon. The model is very rich in representing current and future technologies in both supply and demand sectors and determines investments and market prices endogenously. The agents modelled in separate sub-models are simulated to interact through the exchange of energy/fuel quantities and through prices, leading to simultaneous equilibrium in energy and ETS markets.

The PRIMES power and steam generation module determines the optimal level of power generation and investments under operational and grid constraints. It performs simultaneously optimization of unit-commitment, capacity expansion and DC-linearized power flow over interconnectors. The optimization is inter-temporal and assumes perfect foresight. Interaction with demand (price-elastic behaviour) is ensured in the overall model.

The model covers explicitly the national energy systems of all EU countries as well as their neighbouring non-EU countries Norway, Switzerland, Turkey and the countries of the Balkan region. The time resolution of the model is annual, identifying typical days within a year, modelled as consecutive but discrete load segments, each representing a portion of the year, in hours. The aggregation in time segments takes into consideration daily and seasonal variations of load.

Electricity and steam/heat demand by load segment are inputs from the demand modules of PRIMES. The power sector module determines how this demand will be satisfied, simultaneously considering technology options for power, CHP, distributed steam, distributed heat, and district heating. Every power technology is characterized by the type of fuel, efficiency, cogeneration technique (if applicable), availability, investment or retrofitting potential and operational costs.

Electricity trade between countries is determined endogenously based on economically determined power flows taking into consideration the constraints of the interconnectors. The model simulates a DC linearized power flow problem over a network, with every country being represented by a single node and with multiple interconnectors between the nodes. The model represents approximately 350 interconnectors and it fully incorporates the latest version of the Ten-Year-Network-Development-Plan (TYNDP) of ENTSO-E [10].

Modelling of the decarbonisation context

The scenarios analyzed for the RESDEGREE project are scenarios of high renewables penetration in the EU, ranging from 30% in 2030 and reaching 80% in 2050 in the extreme scenario of the analysis (see chapter 3 on Scenario set-up for more details). Such levels of renewables penetration imply that there is an underlying assumption of "decarbonization", i.e. of the EU reducing very significantly emissions in all sectors of the economy. The scenarios naturally incorporate apart from RES penetration targets greenhouse gas emissions reduction targets of 40% in 2030 and 80% in 2050. Therefore, the scenarios should simulate a general policy and development context that would be consistent with moving towards a low carbon economy.

Decarbonization is a process that requires a series of structural changes in all sectors of the economy; uptake of advanced clean and/or more efficient technologies (in power generation, industrial processes, household energy consumption etc.), very considerable infrastructure developments (in support of RES integration, transport electrification etc.) are indicative examples. Such changes are costly and imply that there are strong drivers to push relevant investments, e.g. a strong policy context that facilitates and coordinates such developments and that provides investors with certainty that future strong emissions reduction will occur, so as to foresee necessary developments and take action on a timely manner.

The PRIMES model incorporates a series of tools that allows for simulating the described conditions of decarbonization: market coordination, good anticipation of the decarbonization process from the investors' perspective, behavioral changes that would result from a stricter policy context in regard to energy consumption, technological advances, etc. These tools are referred to as "enabling conditions" and they are used when the context of the analysis is shifting from a reference or business-as-usual case, and instead assumes a general policy context that would allow the decarbonization of the EU economy.

As this project places focus on power generation, the following paragraphs discuss the enabling conditions of decarbonization for the energy supply, and the reader is referred to the PRIMES model manual [7] for more details on this matter. Decarbonization conditions for the energy supply side include:

- Implementation of policies that would allow for higher uptake of RES technologies, such as facilitation of permitting procedures and higher investment in grids (both high voltage, incl. DC lines for remote wind areas, and smart grids supporting management of decentralized RES and net metering). These conditions, despite not including financial support to RES, imply higher potential at equal cost levels, hence higher uptake of RES technologies, compared to business as usual. The additional potential is mainly in highly decentralized RES (which depend on distribution grid infrastructure) and in large scale offshore wind in remote areas (which depends on long distance DC systems to be also developed).
- Implementation of policies that would allow for higher potential of implementing CCS technologies, such as policies that would enable the timely development of carbon transport and storage infrastructure, as well as policies that would alleviate the public's concerns on safety and environmental issues relating to CCS.

- Implementation of policies relating to biomass related innovation that would allow the development of new generation bio-energy feedstock (basically lignocellulosic crops) at large scale.
- Assumption of technological progress that would enable in the long term the mix of hydrogen and bio-gas in gas supply and the possibility to use hydrogen-based storage for balancing RES power and therefore exploiting variable RES at larger scale.

Modelling of variable RES

Variable RES are treated in a deterministic manner; for every load segment of the model the nominal capacity of RES is reduced by a factor, the value of which depends on the type of RES and the region. This factor represents the resource intensity of variable RES in every load segment. Special care has been taken in order to ensure that the factors applied in every time segment capture all the key characteristics of the RES generation that affect the net load patterns[2] (and ultimately the generation profiles of conventional plants), as well as the frequency with which these characteristics are demonstrated. More specifically they capture the occasions that the energy system would have to meet high ramping rates (up and down) due to RES and the occasions that the system will have to operate at technical minimums (occasions of very low demand coupled with very high generation from RES).

The model's resolution is national; however in-country grid developments that are necessary in support of RES penetration are accounted for in the model through non-linear cost relationships that associate RES development with grid costs. The linkage to the RESlion model allows considering the issues of in-country RES integration in higher detail.

Mathematical configuration

The following equations aim at presenting the above described optimization problem in a nutshell. In the equations, variables are shown in bold font and indices are shown in italics, while the rest are exogenous parameters. For reasons of simplicity the equations include only electricity generation and not steam/heat generation. Moreover, they are limited to key functions of the model and do not show how the model accounts for losses, blending of fuels, carbon prices, the availability of CCS, and other features. Among those are also the endogenous derivation of hydro pumping and endogenous storing of energy in various storage technologies candidate for investment.

$$\min_{\mathbf{G},\mathbf{G^{cp}},\mathbf{P},\mathbf{F}} \ \mathrm{z}\left(\mathbf{G}_{(i,n,s,t)}, \mathbf{G}^{\mathbf{cp}}_{(i,n,t)}, \mathbf{F}_{(i,n,f,s,t)}\right) \qquad (1a)$$

Subject to

$$\sum_{n}\sum_{f}\mathbf{G}_{(i,n,f,s,t)} = \mathrm{C}_{(i,s,t)} + \sum_{b}\left\{\mathrm{M}_{(i,b)}\mathbf{P}_{(b,s,t)}\right\} \qquad \forall i,s,t \qquad (1b)$$

$$\mathbf{P}_{(b,s,t)} = \sum_{i}\left\{\mathrm{Y}_{(b,i)}\left[\sum_{n}\sum_{f}\mathbf{G}_{(i,n,f,s,t)} - \mathrm{D}_{(i,s,t)}\right]\right\} \qquad \forall b,s,t \qquad (1c)$$

$$\mathbf{F}_{(i,n,f,s,t)} = \mathrm{hr}_{(i,n,t)}\mathbf{G}_{(i,n,f,s,t)} \qquad \forall i,n,f,s,t \qquad (1d)$$

$$0 \le \mathbf{G}_{(i,n,f,s,t)} \le \mathrm{ur}_{(i,n,s,t)}\mathbf{G}^{\mathbf{cp}}_{(i,n,t)} \qquad \forall i,n,f,s,t \qquad (1e)$$

[2] Net load: Total load minus the generation from variable RES. It is the load that needs to be met by conventional plants.

$$\mathrm{P}^{\min}_{(b,s,t)} \leq \mathbf{P}_{(b,s,t)} \leq \mathrm{P}^{\max}_{(b,s,t)} \qquad \forall b,s,t \quad (1f)$$

$$\sum_{s} \left\{ \mathrm{hs}_{(s)} \mathbf{F}_{(i,n,f,s,t)} \right\} \leq \mathrm{F}^{\max}_{(i,n,f,s,t)} \qquad \forall i,n,f,t \quad (1g)$$

Indices *i, n, f, s, t* and *b* refer to countries, fuels, load segments, years and interconnectors, respectively. **G**, $\mathbf{G^{cp}}$, **P** and **F** are the variables of the problem and refer to power generation, power capacity, inter-country power flows and fuel consumption.

The objective function (1a) is the minimization of the overall cost, taking into consideration O&M costs of power plants, investment costs of new capacities (annuity equivalent costs) and fuel costs. Equation (1b) ensures that total generation is equal to total demand minus net imports. C denotes electricity demand, which is an input from the demand module of PRIMES, it is therefore treated as a parameter. M is a matrix parameter, containing values 0, 1 and -1 that represent the topology of the network. Equation (1c) determines the power flows on the interconnectors, with Y being the matrix that contains the Power Transfer Distribution Factors (PTDF). Equation (1d) defines the amount of fuel that needs to be consumed in every power plant, with hr being the parameter denoting the heat rate of every power plant. Equation (1e) sets the limits of generation within every country so that it does not exceed its installed capacity, with ur being the utilization rate of every power plant. Equation (1f) ensures that power flows respect the limits of the interconnectors. Similar equations exist in the model to represent net transfer capacities (NTC) between countries. Finally, Equation (1g) ensures that total fuel consumption does not exceed the maximum available quantity F^{max} where applicable.

Pricing of electricity is endogenous (not shown in the equations above) applying different tariffs by sector; loop with demand which responds to prices is established.

Enhancements of the PRIMES model for the RESDEGREE project

Within the context of this project, E3MLab worked towards increasing the time resolution of the model. In particular, E3MLab increased the number of time segments included in the model from 11 to 120, in order to improve the representation of RES as well as load patterns in the simulation.

For this reason E3MLab collected historical data of wind and solar generation from the TSO's of European countries where available and complemented the obtained database with RES generation projections from Eurowind. The data has been statistically processed in order to yield typical cases of wind and solar generation within a year. In particular, the data has been clustered to typical days of strong-weak wind generation and strong-weak solar generation. Typical days are also characterized by the type of day (working day or holiday) and season (winter, summer and spring-autumn combined) as this differentiation affects the load pattern, yielding four categories: working day summer, working day winter, working day spring-autumn and working day-holiday. Typical days also make distinction between the countries of North and South Europe. Overall, every typical day has 6 characteristics, for example, a typical day is working day – winter – weak wind in the South – strong wind in the North – strong solar in the south – weak solar in the North.

This approach yields 32 typical cases. E3MLab narrowed the cases down to 24 by eliminating the cases with very low frequency. The 24 obtained cases cover for the 90% of the cases observed in the database. The 24 hour pattern in every typical day was then clustered in 5 representative time segments, yielding overall 120 time segments.

The analysis employed both versions of the model and the simulation of the scenarios with PRIMES has two phases; the first phase is undertaken with the 11 time segments version and yields the main results of the analysis. The second phase is undertaken with the version of 120 time segments in order to gain more insight on the trends of flows and to assess the robustness of the first results regarding investment requirements for flexibility purposes and trade flows. For this purpose, in the second phase of simulations, the level of investments of variable RES capacities has been fixed to the level of the results from the first model round. This approach was followed in order to test whether the structure of the power system with such high level of RES as projected with the standard version of the PRIMES model in the scenarios of the analysis is feasible from an operational perspective when considering in more detail the variability of generation and load patterns. Moreover, this approach allows to decrease the number of decision variables and thus reduce computing time, as PRIMES simulates simultaneously all countries of the EU and non-EU countries, and with increasing resolution (approximately ten times higher).

2.2. The RESlion model

Introduction

The energy transition towards a renewable energy based system changes the supply and demand structure of the European electricity system already today. With increasing fluctuating feed-in from RES the influence on site selection of generation capacities will become a more important issue in the forthcoming years as it affects the electricity flows. Therefore, the RESlion model is used in this project to analyse these aspects in detail for the overall European context which is evaluated by the PRIMES model.

The future use and integration of RE technologies into the energy system at the European level are extensively discussed in several policy papers (see [13] and [15]). For the German case, [16] present a long-term vision of the German electricity system in a European context. If developments in international electricity systems are analysed over a large area (such as the European Union), comprehensive energy system models are used to indicate and forecast potential trends and developments of the energy systems. One of these large energy system models is PRIMES as seen in the last chapter. These models enable the analysis of national changes in generation portfolios and electricity flows between countries for the European context by covering the EU-28 member countries plus further neighbouring countries. However, modelling of large (energy) systems implies many simplifications regarding geographical and temporal resolution.

Therefore, different approaches are developed to optimize the runtime of energy models containing the expansion planning and operation in the electricity system as in [16] or [1]. As national developments, such as in the case of the energy transition, show regionally different effects regarding the distribution and generation of electricity generating technologies, general (national) results have to be adjusted and analysed on a smaller geographical area. Therefore, energy system models with higher regional resolution allow a more detailed analysis of the in-country developments of national energy systems. Coupling the RESlion-Europe optimization model [17][18] with scenario results of PRIMES is an option to detail PRIMES' results on a national level. Furthermore, requirements for the whole system can be evaluated to specify additional system effects due to the higher regional resolution.

Therefore, the RESlion modelling approach uses higher geographical resolution for the deployment and use of renewable energy. This should help to elaborate potential impacts on conventional power plants as well as the grid structure of the whole power system. Certainly, regional transmission capacity planning is influenced by higher shares of RES. This is also neglected in many studies that cover only international interconnectors between countries.

Key challenges in terms of modelling and evaluation in this project are the following research topics:

(1) Development of a new integration approach for RES generation and RES potential for Europe with high resolution, in particular detailed modelling of 27 regions in Germany and 9 regions in Greece

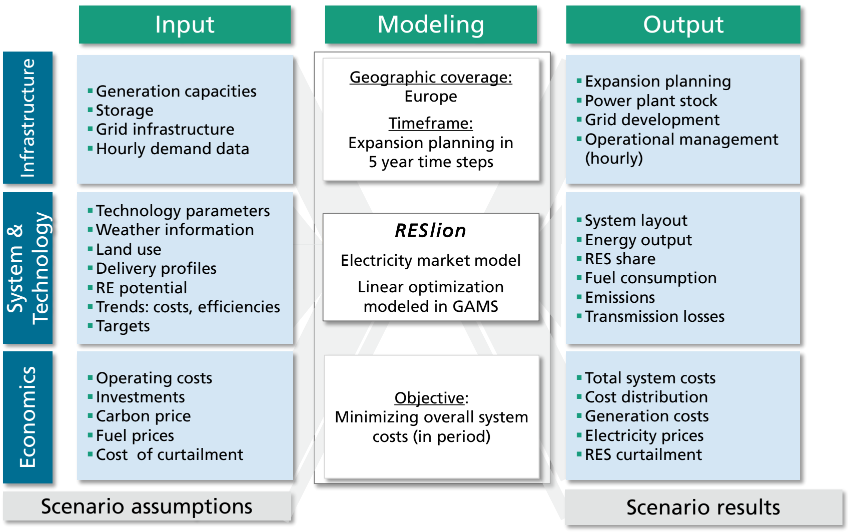
(2) Creation of the modelling interfaces to PRIMES
(3) Analyse of national developments in Germany and Greece regarding generation expansion, grid expansion, use of intermittent renewable generation and back-up flexibilities such as gas turbines and storage systems

In the following, the modelling approach of RESlion and the RES potential analysis using GIS is presented.

Model approach and description

RESlion (RESlion-Europe) is an expansion and unit-commitment optimization model for the power sector. The current status of the model covers countries in Northern, Central and Southern Europe: Norway, Sweden Denmark, Germany, Netherlands, Belgium, Luxembourg, France, Switzerland, Italy, Austria, Greece, Czech Republic and Poland. The model covers expansion planning of power generation technologies including renewable energy sources and transmission capacities (net transfer capacity - NTC) over the next 40 years. The problem is implemented as a linear program which minimizes total system costs consisting of expenditures for construction and operation of the power system. As a key issue this modelling approach includes the existing conventional power plant system in the analysis and connects it with a high-resolution simulation of renewable energy generation. Also grid extensions between local areas via HVAC lines and the electricity transmission via HVDC lines between Central and Southern Europe are linked in the investment model. The results are constraint by many technical and economic constraints as well as RES targets or CO_2 reduction targets for a certain year. The expansion problem can be solved for different years between today and 2050. The relation between model input and model output is displayed in Figure 2.

Figure 2: Input and output of the RESlion optimisation model



The optimization model RESlion is developed in GAMS and has the following key elements:

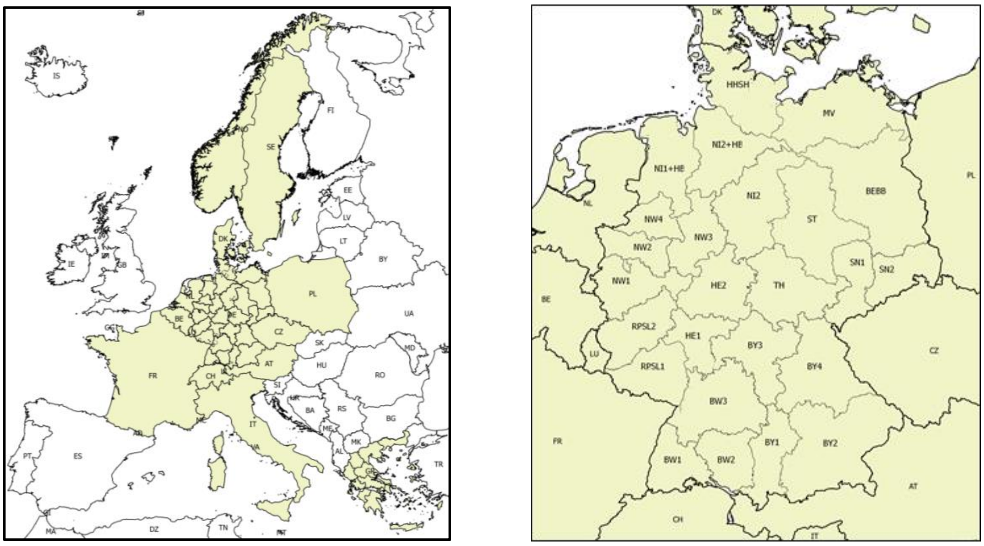
- Cost minimization approach takes into account costs for construction and operation of renewables, conventional power plants, transmission capacities within and between countries, storage systems as well as other flexibility options
- Regional specific expansion of renewables and conventional power plants
- Integrated expansion planning with perfect foresight over 20 to 40 years
- Hourly operation of power plants is included in the expansion planning with a reduced and preliminary approach

- Integration of potentials of renewable energy sources in all covered European country by using a GIS approach
- Technology specific learning curves for cost projection until 2050
- Use of sub-national grid structure for the transmission grid including transmission losses

The expansion problem of the electricity generation technologies and the transmission grid is modelled with a high geographical resolution by splitting Germany in 27 and Greece in 9 sub-regions. The optimization model RESlion (RESlion-Europe) covers the countries in Northern, Central and Southern Europe: Norway, Sweden Denmark, Germany, Netherlands, Belgium, Luxembourg, France, Switzerland, Italy, Austria, Greece, Czech Republic and Poland. Each region in Germany is further subdivided to allow a more detailed installation of photovoltaic and wind power plants. For the purpose of this project, Greece is split into 9 model regions (similar to Germany). All existing high voltage transmission lines between two regions are included in the database of current infrastructure. Within sub-regions electricity exchange is loss-free. All existing generation capacities are indexed to one region by considering their geographic location.

Figure 3: Geographical scope of the RESlion-Europe model

Europe Germany



The modelling approach includes renewable energy potentials per region and optimizing the renewable energy and conventional power plant portfolio under demand, supply and transmission capacity constraints.

The RESlion model calculates the regional distribution, the capacities per technology as well as necessary extension of the transmission grid capacities. A very detailed GIS analysis for RES potential is used to calculate the regional distribution of the power plants. The inputs from PRIMES contain the CO_2 and fuel prices as well as the electricity demand. Within this scenario framework the cost optimal electricity generation portfolios for Germany and Greece are calculated using high resolution RES potentials and weather information of the sub-regions.

Total system costs of the electricity system are minimized in the objective function of the optimization model. The objective function considers investments (I) in power plants, transmission lines or storages as well as their operation costs (*OC)*.

$$minimize \qquad TOTAL.SYSTEM.COSTS = I + OC$$

Investments for new constructions consist of the costs from new power plants, transmission lines and energy storages (*NEW.CAP*$_{EP,year}$). The size of each object (energy project EP) is multiplied by the specific technology cost (in EUR/kW) of the reference system in the year of construction (*tech.cost*$_{EP,year}$) and the annuity factor ($a_{i,LT}$).

$$I = int.years * \sum_{EP} \sum_{year} \left[NEW.CAP_{EP,year} * a_{tech} * \frac{tech.cost_{EP,year}}{disc_{year}} \right]$$

Operation costs in the model cover fixed operation costs (*fix.op.costs*$_{EP}$), variable costs (var.*op.costs*$_{tech}$, *transmission.costs*$_{line}$, *var.op.costs*$_{storage}$), fuel costs (*fuel.costs*$_{tech,fuel}$) depending on the power plant efficiency (*tech.eff*$_{tech}$), costs for buying CO_2 emission allowances (*factor.CO2*$_{tec}$), costs for load change (*load.change.costs*$_{tech}$) and for operating in a part-load mode (*part.load.costs*$_{tech}$).

$$\begin{aligned}
OC = {} & int.years * \sum_{infra} \sum_{year} \left[INST.CAPP_{EP,year} * fix.op.costs_{infra} / disc_{year} \right] && \textit{Fixed costs} \\
& + (int.years * 8760 / number.hours * number.ears\ ) \\
& * \Bigg[\sum_{tech} \sum_{t} \Big[\left[TEC.GEN_{tech,t} * var.op.costs_{tech} \right] && \textit{Var. costs} \\
& + \left[TEC.GEN_{tech,t} * fuel.costs_{tech,fuel} / tec.eff_{tech} \right] && \textit{Fuel costs} \\
& + \left[\left(LOAD.CHANGE.UP_{tech,t} + LOAD.CHANGE.DOWN_{tech,t} \right) \right. && \textit{Load change costs} \\
& \left. * load.change.costs_{tech} \right] + \left[PART.LOAD_{tech,t} * part.load.costs_{tech} \right] && \textit{Part-load costs} \\
& + \left[TEC.GEN_{tech,t} * factor.CO2_{tech} \right] \Big] / disc_{t.year} && \textit{CO2 costs} \\
& + \sum_{line} \sum_{t} \left[LINE.TRANS_{line,t} * transmission.costs_{line} \right] / disc_{t.year} && \textit{Transmission costs} \\
& + \sum_{storage} \sum_{t} \left[STOR.GEN_{storage,t} * var.op.costs_{storage} \right] / disc_{t.year} \Bigg] && \textit{Var. costs (storage)}
\end{aligned}$$

Each power plant has a limit of its hourly **maximum generation**.

$$TEC.GEN_{tech,t.year} \leq INST.CAPACITY_{tech,year} * availibility_{tech}, \qquad \forall\ tech, t.year, year$$

New (*NEW.CAP*$_{EP,year}$), existing (*INST.CAP*$_{EP,year}$), and closing (*CLOSE.CAP*$_{EP,year}$) objects are linked by the following **system inventory** constraint.

$$INST.CAP_{EP,year} = NEW.CAP_{EP,year} + INST.CAP_{EP,year-1} - CLOSE.CAP_{EP,year}, \quad \forall\ EP, year$$

Energy balance is set by electricity demand of consumers (*demand*$_{r,t}$) per region (*r*) and generation per region and exchange of electricity with neighboring regions (*IN.OUT*$_{r,t}$).

$$demand_{r,t} * (1 + loss + res) = \sum_{tech\ in\ r}^{N} TEC.GEN_{tech,t} - IN.OUT_{r,t} - EL.CURT_{r,t}\ , \forall\ r, t, eu$$

Electricity exchange of a regions r_j with its neighboring regions depends on the volume of outflows ($LINETRANS_{line,t}$, all lines with start r_j) to other regions and inflows (all line with end r_j) from other regions. Transmission line losses ($loss_{line}$) depend on the distance of the geographic centers of the two regions which are connected by transmission lines.

$$IN.OUT_{r,t} = \sum_{line\ with\ start(r)} [LINE.TRANS_{line,t} * (1 + loss_{line})] - \sum_{line\ with\ end(r)} LINE.TRANS_{line,t}, \qquad \forall\, r, t$$

Electricity transmission between regions is limited to the transmission capacity which is installed ($ex.line_{line}$) in the past or is constructed newly ($NEW.LINE_{line,year}$). In this constraint, line losses and a security margin ($l.sec_{line}$) are considered.

$$LINE.TRANS_{(line,t.year)} * (1 + loss_{line} + l.sec_{line}) \leq ex.line_{line} + NEW.LINE_{line,year}, \forall line, t.year, year$$

Electricity generation of intermittent RES power plants is implemented by using specific generation profiles per location.

$$TEC.GEN_{RES,t.year} = profile.ee_{RES,t.year} * \ INST.CAP_{RES,year}\ , \qquad \forall\ RES, t.year, year$$

These formulas are the backbone of the electricity system model RESlion. However, more equations are necessary to completely model the expansion and operation of all energy projects in the system [18].

Modelling of renewable energy in energy system model RESlion

To be able to analyse the system development for Germany and Greece deeply, the RES potential in both countries is analysed by using a GIS approach. In the literature, different approaches to integrate RES generation and RES potentials into an energy system model are used. One option is to use historical feed-in data of RE technologies on a country level and to scale up these profiles depending on the further RE technology expansion. Another option uses generation profiles for each technology based on weather data. In addition, extensive geographical information system (GIS) modelling approaches using large geographical datasets are developed to deeply analyse the RES potentials in the EU, North Africa or the whole world ([19], [20], [21]). However, it is necessary to optimally represent RES potential and the variety of generation profiles of RES at many different locations in Germany and Greece. Furthermore, the future expansion in both countries should be independent from the current distribution of technologies and the absolute number of full load hours. This aspect has been rarely taken into account in existing approaches of implementing RE generation in energy system models.

To analyse the regional RES potential in Germany and Greece (as well as in the neighbouring countries), the following data is included in the GIS analysis, which elaborates suitable land areas for onshore wind power and ground mounted PV. Rooftop PV is also accessed by identifying available urban areas and potential roof areas with the data shown in the following Table I.

By using the Corine Land Cover data suitable land areas are identified and technology specific suitability factors are allocated to them. Furthermore, geographic elevations, slopes as well as protected areas are excluded from the analysis. With regard to the wind energy potential, buffers around certain areas such as airports (5 km) are also considered. Individual suitability factors depending on the land use categories as in [18] and [19].

Table 1: Data of GIS analysis

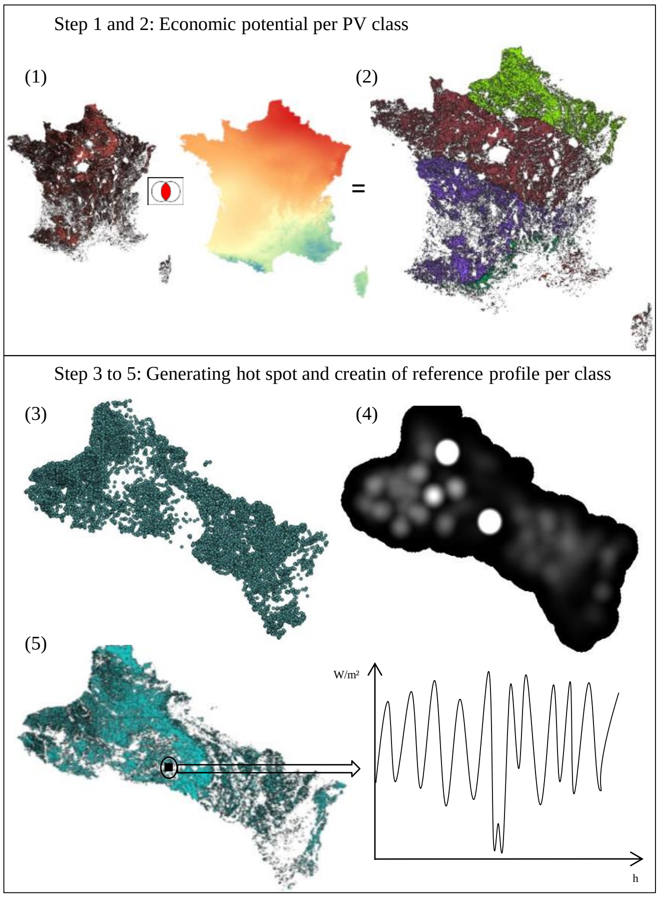
Data	Description	Reference
CORINE Land Cover 2006	Inventory of land cover data in 44 classes	EEA (2006)
Natura 2000	Ecological network of protected areas in the EU	EEA (2013)
World Database on Proteceted Areas	Ecological network of protected areas in the world used for Norway and Switzerland	WDPA (2015)
SRTM 90m digital elevation model	Global elevation data mosaiced in 3 arc seconds	SRTM (2004)
USGS GTOPO30 digital elevation model	Global elevation data mosaiced in 30 arc seconds used for Norway and Sweden	USGS (1996)
Regions of Europe	Administrative borders	GADM (2012)
Solar radiation in PVGIS	Yearly average solar radiation on a optimal inclined surface between 1981-1990	JRC (2004)
ERA-40	Yearly average wind speed between 1987-2002 used for EU	NCAR (2003)
DWD Data	Yearly average wind speed between 1981-2000 used for Germany	DWD (2013)
Climate Research Unit (CRU)	Yearly average wind speed between 1961-1990 used or Greece	New et al. (2002)
Meteonorm	Hourly wind and PV Data of a typical meteorological year on the basis of weather data between 2000-2009	Meteotest (2014)

The following steps are identified to be necessary to come from a detailed GIS analysis to a more sufficient integration of RES generation in the energy system model RESlion:

1) Calculation of available potentials for RES per model region reduced by specific suitability factors in km² using information of current land use (Corine land cover) and average weather conditions per raster element.
2) Detailed RES potential related to weather conditions by building five weather classes per region (e.g. class 1: wind speeds 3.0 – 4.0 m/s, class 2: wind speeds 4.0 – 5.0 m/s).
3) Identifying hot spots per weather class weighted by the available area per land use category (areas with high potential within one model region).
4) Selection of a reference site (hot spot) for a region with class specific potential. In case the hot spot is not located on a suitable area, the nearest suitable area is chosen.
5) Implementation of a site specific hourly weather profile per class and model region in the energy system model.
6) Implementation of the RES potential per class and model region in the energy system model.
7) Repeat step 3 to 6 until all classes and all regions are integrated in the energy system model.

The process described above is illustrated in Figure 4 which shows the RES potentials for one model region (France) and the search of reference sites, with their specific generation profiles, for one class. The white spots in (4) represent the areas with the highest density of suitable areas (hot spots) in a class of which the maximum is chosen (5).

Figure 4: RES potential and specific generation profiles with a hot spot approach



In the next step, RES potential with its specific hourly RES generation profile in each model region for Germany, Greece and the other countries are integrated in the optimization model RESlion. This approach which is used in the scenario model runs has the advantage that the optimization model decides which technology and its site conditions (i.e. generation profile) are most suitable to the demand and supply system of one region or the whole system. By including the RES potential per weather class and region, the model is limited to use a specific class only up to its potential.

RES potential in Germany, Greece and neighbouring countries

The results of potentially suitable areas for Wind and PV (ground mounted and rooftop) of each country are displayed in Table 2. It has to be noticed that in the aggregated results also weather classes with low solar or wind potentials are included. Some of the weather classes with low wind speeds or solar irradiation do not provide enough resources to allow economic operation of RES power plants. Three exemplary modelling regions (France, Mecklenburg-Vorpommern (GER) and Euboea (GR)) are presented in Table 2. The results show, that the highest solar irradiation or wind speeds can only be found in small land areas (see weather class 5). Especially for wind, this finding is important since high RES scenarios will mostly exceed RES potential of the best class.

As illustrated in Figure 5 and Figure 6 (all regions in Germany), the reference sites are allocated throughout the model regions according to the highest density of suitable areas within the different classes gained by the heat map approach.

Figure 5: Reference sites of weather classes for the regions France, Mecklenburg-Vorpommern and Euboea

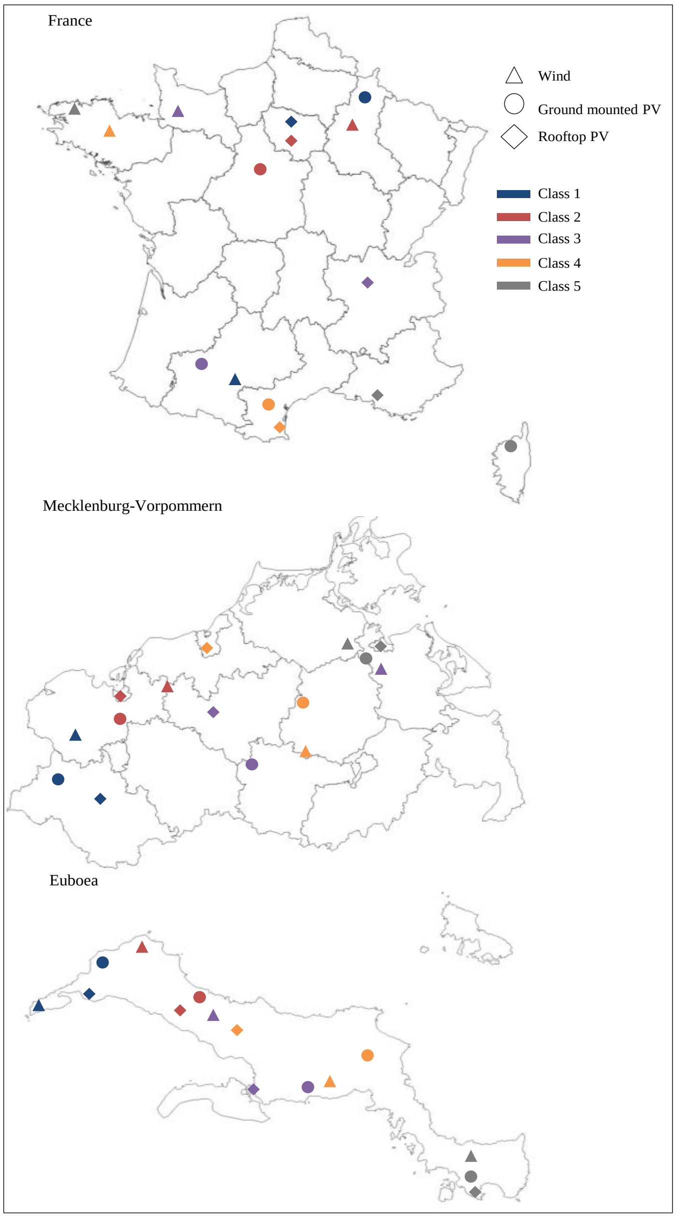


Figure 6: Reference sites of weather classes for the regions in Germany

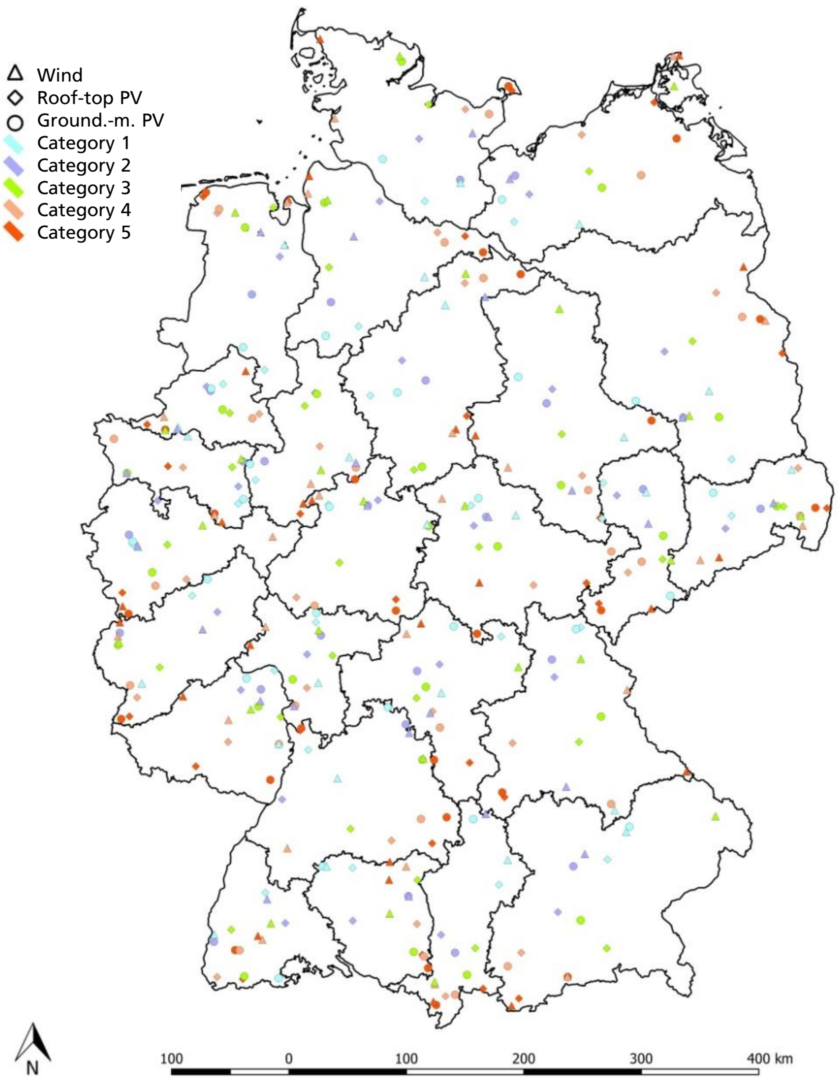


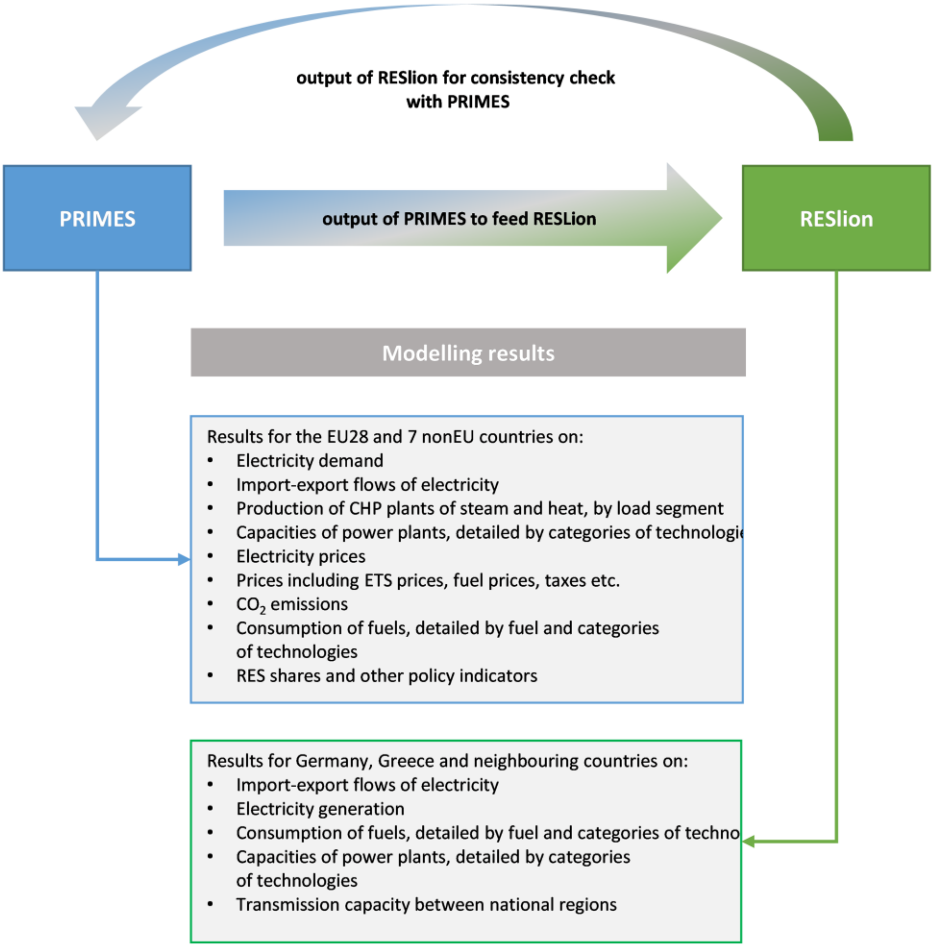
Table 2: RES potential per country (region) in km² (exemplary in detail for France, Mecklenburg-Vorpommern (GER) and Euboea (GR))

Rooftop PV		
Area	***Range* (kWh/m²/a)***	***Suitable Area (km²)***
Belgium (30)	1074.0-1170.0	60.83
Netherlands (31)	1078.5-1176.5	49.14
Luxembourg (32)	1127.0-1184.0	2.30
Switzerland (34)	1174.0-1640.0	26.21
Italy (35)	1214.0-2025.0	138.87
Austria (36)	1146.0-1779.0	39.56
Czech (37)	1095.0-1265.0	48.27
Poland (38)	1119.0-1230.0	121.12
Denmark (39)	1085.5-1174.0	30.95
Norway (40)	861.0-1054.5	25.12
Sweden (41)	1026.0-1168.0	61.39
Germany	1065.5-1482.0	287.91
Greece	1457.0-1961.0	26.92
Ground mounted PV		
Area	***Range* (kWh/m²/a)***	***Suitable Area (km²)***
Belgium (30)	1074.0-1178.0	101.86
Netherlands (31)	1075.0-1180.0	169.99
Luxembourg (32)	1125.0-1178.0	6.16
Switzerland (34)	1130.0-1810.0	20.12
Italy (35)	1319.0-2039.0	1373.57
Austria (36)	1090.0-1730.0	194.81
Czech (37)	1105.0-1266.0	352.47
Poland (38)	1117.0-1248.0	1479.58
Denmark (39)	1076.0-1178.0	249.76
Norway (40)	804.0-1158.0	1271.31
Sweden (41)	920.0-1166.0	432.32
Germany	1065.0-1619.0	1632.67
Greece	1465.0-1961.0	346.03
Wind		
Area	***Range** (m/s/a)***	***Suitable Area (km²)***
Belgium (30)	4.43- 8.31	948.39
Netherlands (31)	5.12-12.01	4289.01
Luxembourg (32)	4.26-6.72	118.85
Switzerland (34)	2.34-4.84	2038.27
Italy (35)	2.17-8.98	31926.59
Austria (36)	2.25-6.60	4837.73
Czech (37)	3.80-6.64	7589.20
Poland (38)	3.11-9.01	40958.73
Denmark (39)	6.04-11.87	29857.96
Norway (40)	2.01-12.04	50248.70
Sweden (41)	2.56-13.14	38574.27
Germany	2.65-11.54	32227.37
Greece	3.13-11.35	21804.39
* Yearly average radiation on optimally-inclined photovoltaic modules		
** Yearly average wind speed at 100 m hub height		

Rooftop PV		
Area	***Class* (kWh/m²/a)***	***Suitable Area (km²)***
France (33)	1 (1118.0-1266.0)	75.31
	2 (1266.0-1414.0)	83.22
	3 (1414.0-1562.0)	70.32
	4 (1562.0-1710.0)	14.30
	5 (1710.0-1858.0)	26.30
Mecklenburg-Vorpommern (25)	1 (1114.0-1130.4)	0.80
	2 (1130.4-1146.8)	1.78
	3 (1146.8-1163.2)	1.29
	4 (1163.2-1179.6)	3.85
	5 (1179.6-1196.0)	2.25
Euboea (46)	1 (1666.0-1690.0)	0.05
	2 (1690.0-1720.0)	0.19
	3 (1720.0-1750.0)	0.26
	4 (1750.0-1780.0)	0.22
	5 (1780.0-1810.0)	0.14
Ground mounted PV		
Area	***Class* (kWh/m²/a)***	***Suitable Area (km²)***
France (33)	1 (1118.0-1273.0)	590.14
	2 (1273.0-1428.0)	1052.54
	3 (1428.0-1583.0)	576.45
	4 (1583.0-1738.0)	103.37
	5 (1738.0-1893.0)	50.49
Mecklenburg-Vorpommern (25)	1 (1111.0-1128.2)	11.49
	2 (1128.2-1145.4)	20.45
	3 (1145.4-1162.6)	18.77
	4 (1162.6-1179.8)	47.71
	5 (1179.8-1197.0)	22.97
Euboea (46)	1 (1640.0-1682.4)	0.33
	2 (1682.4-1724.8)	0.37
	3 (1724.8-1767.2)	2.23
	4 (1767.2-1809.6)	1.55
	5 (1809.6-1852.0)	0.46
Wind		
Area	***Class** (m/s/a)***	***Suitable Area (km²)***
France (33)	1 (2.25-4.11)	6872.66
	2 (4.10-5.96)	29176.71
	3 (5.96-7.82)	8680.66
	4 (7.82-9.67)	834.58
	5 (9.67-11.53)	159.52
Mecklenburg-Vorpommern (25)	1 (5.18-6.37)	498.99
	2 (6.37-7.56)	2088.38
	3 (7.56-8.75)	126.59
	4 (8.75-9.94)	12.18
	5 (9.94-11.14)	0.51
Euboea (46)	1 (4.30-4.94)	4.32
	2 (4.94-5.58)	181.77
	3 (5.58-6.23)	258.42
	4 (6.23-6.87)	301.21
	5 (6.87-7.52)	24.42
* Yearly average radiation on optimally-inclined photovoltaic modules		
** Yearly average wind speed at 100 m hub height		

2.3. Coupling of PRIMES and RESlion models

Figure 7: Coupling of PRIMES and RESlion models for the RESDEGREE project



Output of PRIMES to feed RESlion

- Electricity demand
- Import-export flows of electricity
- Production of CHP plants of steam and heat, by load segment
- Capacities for the power plants, detailed by categories of technologies
- Electricity prices
- Prices including ETS prices, fuel prices, taxes etc.
- CO_2 emissions
- Consumption of fuels, detailed by fuel and categories of technologies
- Various indicators, RES shares, CHP ratios, average efficiency.
- NTC values

Output of RESlion for consistency check with PRIMES

- Import-export flows of electricity
- Electricity prices
- Consumption of fuels, detailed by fuel and categories of technologies

The coupling of the two models consists of defining the flow of information between the two models. It sets the sequence of model runs and which elements of the two models serve as inputs to the other and which as final outputs of the analysis. Figure 7 summarizes the flow of information between the two models.

The PRIMES model is run first and it provides a description of the national energy systems, including power flow allocation of interconnection capacities, for every five years until 2050 and limited to the time segmentation of the model. It yields the structure of the power generation system at a country level (installed capacities, investments and decommissions), electricity demand, prices, electricity import-export flows as well as a variety of indicators relative to the operation of the system. These outputs are then introduced in the RESlion model which performs optimisation of the energy systems of Greece and Germany specifically and yields a more detailed overview of the planning and operation of power generation capacities due to its higher temporal and regional resolution. However, the model considers the neighbouring countries as well.

It performs hourly unit commitment, handling renewables system integration in a detailed planning and operating modelling and capturing technical constraints of system operation including ancillary services.

This approach allows consistently modelling the integration of the Greek and German energy systems within the IEM, which we wish to examine within this project; RESlion looks very closely within every country and PRIMES ensures the modelling of other countries that participate in the integration. With the coupling of the models we have achieved a very accurate modelling of complementarities between Greece and Germany regarding renewables deployment and their system support and balancing requirements.

It should be noted that RESlion and PRIMES have some common outputs, such as electricity generation, trade flows and fuel consumption. The comparison of these outputs allows for consistency checks between the results of the two models.

3. Scenario set-up

The scenarios analysed for the RES-DEGREE project are built around two main aspects: a) varying the assumptions of RES target for the EU, and b) varying the assumptions on the level of international interconnections. With the above in mind the scenario set-up of RES-DEGREE includes overall 6 scenarios, 3 main scenarios, two sensitivities and a reference scenario. Table 3 below summarizes the scenario set-up and is followed by a description of every scenario.

Table 3: The scenario set-up of the RESDEGREE project

	Reference	**RES30-50**	**RES35-65**	**RES35-80FDC**
RES target for Europe (EU-28)	Achievement of 2020 RES target	RES share reaching 30% in 2030 and 50% in 2050	RES share reaching 35% in 2030 and 65% in 2050	RES share reaching 35% in 2030 and 80% in 2050
Interconnections developments	TYNDP	Additional interconnections to TYNDP	Additional interconnections to TYNDP	Additional interconnections to TYNDP
DC grid	-	-	Medium scale development of DC grid	Full scale with DC super grid, and DC linking GR and DE
Sensitivity	-	RES30-50 with additional DC linking GR and DE (RES30-50_B)	RES35-65 with additional DC linking GR and DE (RES35-65_B)	-

- **Reference scenario**: The Reference scenario is a scenario of current trends of developments. It incorporates all currently adopted policies and measures at the EU level and at national level reach their successful implementation, including the achievement of the 20-20-20 targets. In regard to interconnections, the Reference scenario assumes that the European network evolves according to the Ten-Year-Network-Development Plan of ENTSO-E. This scenario will not include a RES target beyond 2020. It will provide an overview of the developments in the EU but also in Greece and Germany considering only what is currently known.
- **RES30-50:** This scenario will be designed so as to achieve a 30% target of RES in 2030 and a 50% target in 2050. This scenario will be built under the assumption that the EU is on a decarbonisation path so that it describes a context that could incorporate the high RES assumption that we wish to explore. The decarbonisation assumptions will include a 40% GHG emissions reduction target by 2030 (relative to 1990) and 80% in 2050. Under these assumptions, the PRIMES model will simulate the development of the energy sector, including the required level of investment that should be undertaken to expand the network beyond the TYNDP in order to achieve the increased penetration of RES. The RESlion model will yield with the detailed overview of the network developments and the operation of RES within Greece and Germany.
- **RES30-50_B (sensitivity analysis to RES30-50)**: This sensitivity scenario will examine the effect of increasing interconnections between Greece and Germany in the context of achieving the RES target of RES30-50. In particular, an additional DC link between Greece and Germany will be introduced. The capacity will be determined through the analysis of RES30-50 scenario (as part of WP4). The PRIMES and RESlion models will rerun, with the same RES targets as RES30-50. The results will be compared to RES30-50 results in regard to energy system costs, and other aspects.
- **RES35-65 and RES35-65_B**: The same approach as for RES30-50 and RES30-50DC is followed, only the RES targets are higher for both 2030 and 2050 (35% and 65% respectively). The impact of increasing the RES penetration will be demonstrated. Moreover, our conclusions on the effects of the direct linkage between Greece and Germany will be tested and enhanced through exploring how they are altering with increasing RES penetration.
- **RES35-80FDC:** This scenario will be developed under the assumption that RES share in 2050 is reaching 80% and that there is full-scale development of the network, with DC super grid and North Sea interconnections. The same analysis as in RES30-50 and RES35-65 will be undertaken. This scenario will serve as a maximum benchmark and it will complete our overview of the interactions between high RES and increased interconnections.

The EU RES shares that define the scenarios regard the whole of the economy (energy supply and demand sectors) and have been imposed on the PRIMES model as constraints. PRIMES determines endogenously the investments that are required in every country in order to meet these EU RES targets in both power generation and demand sectors; hence the RES share in electricity of every country is an output of the model and is such that the distribution of RES by sector is cost-efficient.

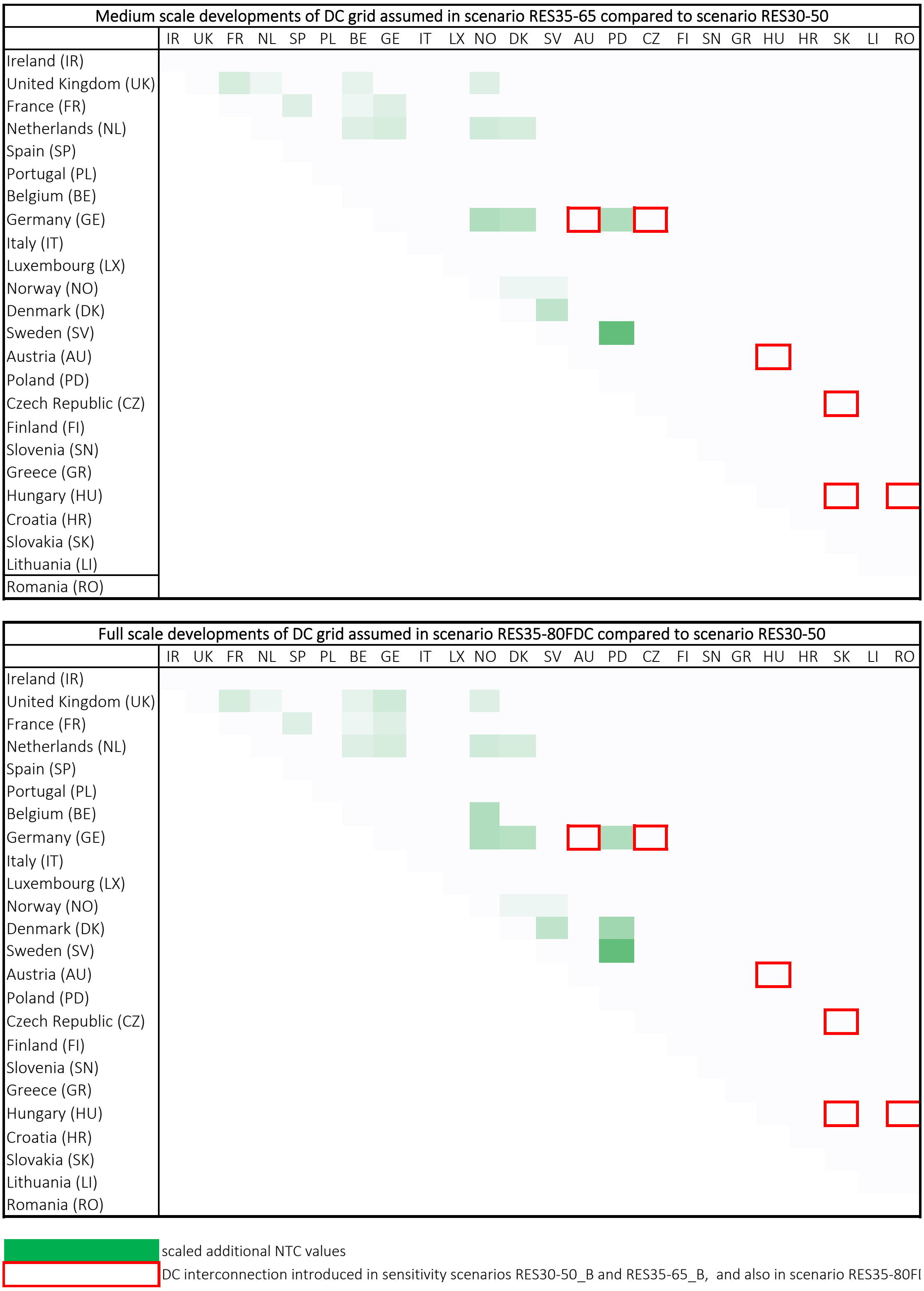
The scenarios assume a general policy context which favours RES development within a pathway towards a low carbon economy in the EU. Drivers are assumed to be the RES supporting schemes and the EU ETS. The modelling with PRIMES reflects the implementation of direct RES aids (such as Feed-in-tariffs) in every MS, the implementation of other national policies that facilitate RES penetration (e.g. on priority grid access and grid developments) and finally the implementation of yet to be defined policies for achieving legally binding national targets, through modelling their marginal cost. The impact of the

ETS market rules on ETS carbon prices is endogenously projected in PRIMES and depends on RES and other clean technology deployment in the power and industrial sectors.

All scenarios assume successful implementation of the TYNDP. In addition, the RES30-50 AND RES35-65 scenarios assume higher NTC values of existing interconnectors, while the RES35-80FDC assumes also the development of a DC super grid which exploits fully the North Sea wind offshore potential. The additional interconnectors are assumed to develop mainly offshore linking Norway and Denmark to the EU mainland. The choice of including these assumptions has been made because a context with aggressive RES penetration would otherwise entail considerable inefficiencies and costs for the national energy systems and is considered unrealistic. The existence of the DC super grid in the RES35-80FDC scenario affects more Germany than Greece due to its topology, allowing Germany to reap resource availability benefits from the off-shore wind capacities in the North Sea.

In the sensitivity cases RES30-50_B and RES35-65_B we have introduced a DC linkage between Greece and Germany passing through the countries of the Balkan region. In particular, we have introduced two lines, a 4GW DC line that passes through F.Y.R. of Macedonia, Serbia, Hungary and Austria, and a 6GW DC line passing through Bulgaria, Romania, Hungary, Slovakia, and Czech Republic. In the modelling with PRIMES intermediate countries are allowed access to the introduced lines. We have chosen to include DC lines instead of AC due to their higher controllability which would bring higher benefits in terms of flexibility for the systems of both countries. The lines are assumed to be put in operation gradually from 2025 onwards, operating at full capacity in 2050.

Figure 8: Graphic representation of scenario assumption on DC grid developments



4. Modelling results of the PRIMES model

In the following we present key findings of the analysis with the PRIMES model[3]. We will focus on the structure of the system in a context of high penetration of RES, looking at the EU28 as a whole, and the Greek and German power systems separately. We will then explore the effects for the Greek and German power systems of introducing an interconnection between them, and we will also discuss spill-over effects of the enhanced system for the rest of the EU28. Finally, we will assess the economic viability of the introduced interconnection.

4.1. The EU28 power system with high RES development

Figure 10 demonstrates the structure of the power generation capacity for the EU28 as it is formed for the scenarios analyzed. The figure shows that the share of variable RES (namely wind onshore, wind offshore and solar capacities) in total installed capacity ranges from 40-50% already in 2030 and reaches 50-70% in 2050. Respective figures of variable RES in generation are given in Table 4. Such a high contribution of variable renewables implies considerable system reliability threats for the national energy systems. This is because increasing variable RES introduces significant fluctuations on the load curve, on both daily and sub-hourly time scales (see also Introduction for a description of the impact of variable RES on the variability of load). Dealing with such fluctuations calls for plants that can provide flexibility services and storage capabilities. For thermal plants this implies alternating regularly between the technically minimum and stable generation power levels, with frequent starts/stops and fast ramping capabilities. The thermal plant technologies that cope with these requirements are gas peaking plants, diesel oil generators, as well as combined cycle gas plants (CCGT). Hydro power plants with pumped storage also provide flexibility services, however the untapped potential for development of such capacities is limited.

Table 4: EU28 shares of RES (total RES and variable) in electricity generation

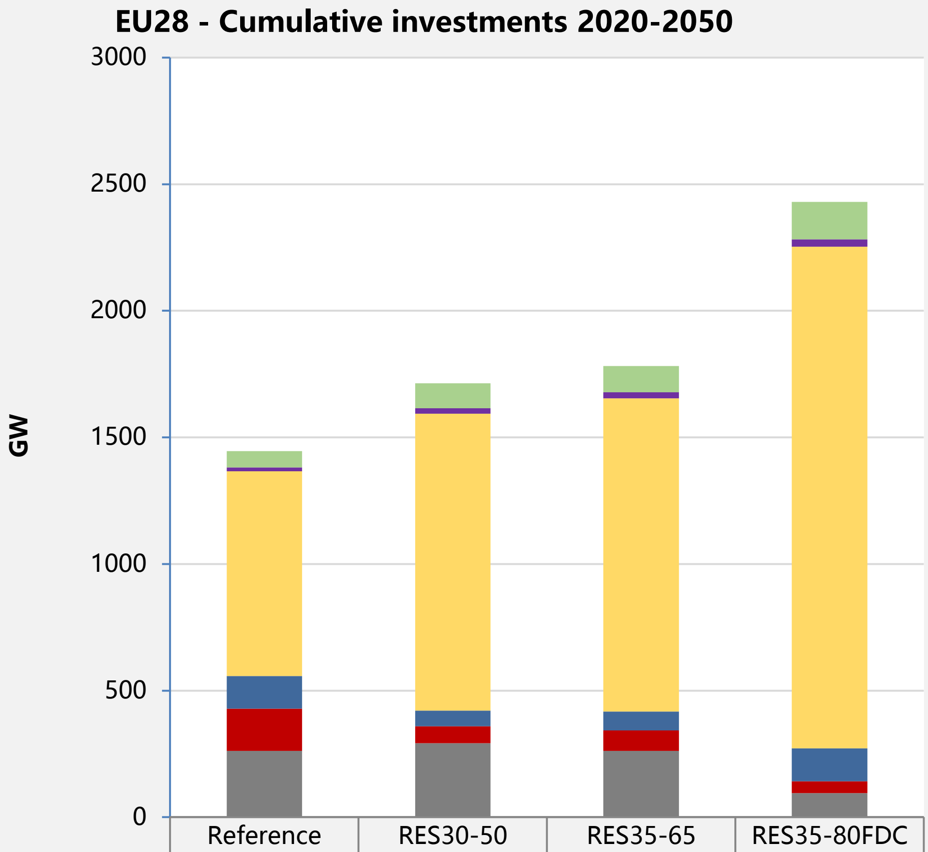
EU28 - RES share in electricity generation (%)			
	2020	2030	2050
Reference	36	44	52
RES30-50	38	59	69
RES35-65	38	60	73
RES35-80FDC	43	66	93
EU28 - Variable RES share in electricity generation (%)			
	2020	2030	2050
Reference	24	33	39
RES30-50	25	43	53
RES35-65	25	44	56
RES35-80FDC	29	50	73

The above is demonstrated in the scenario results of the projected investments. Figure 9 which presents the projected investments of every scenario reveals several interesting aspects of the transition towards an energy system in Europe based on RES. Notice that the overall level of investments is increased in the scenarios with high RES penetration relative to the Reference scenario. This can be attributed to several

[3] The results are presented for all scenarios of the analysis, which are described in detail in chapter 3. For a summary of the key characteristics of the scenarios the reader is referred to Table 3. The discussion of the results focuses on the scenarios with high RES penetration (RES30-50, RES35-65 and RES35-80FDC), however the Reference scenario results are also provided to serve as a basis for comparison.

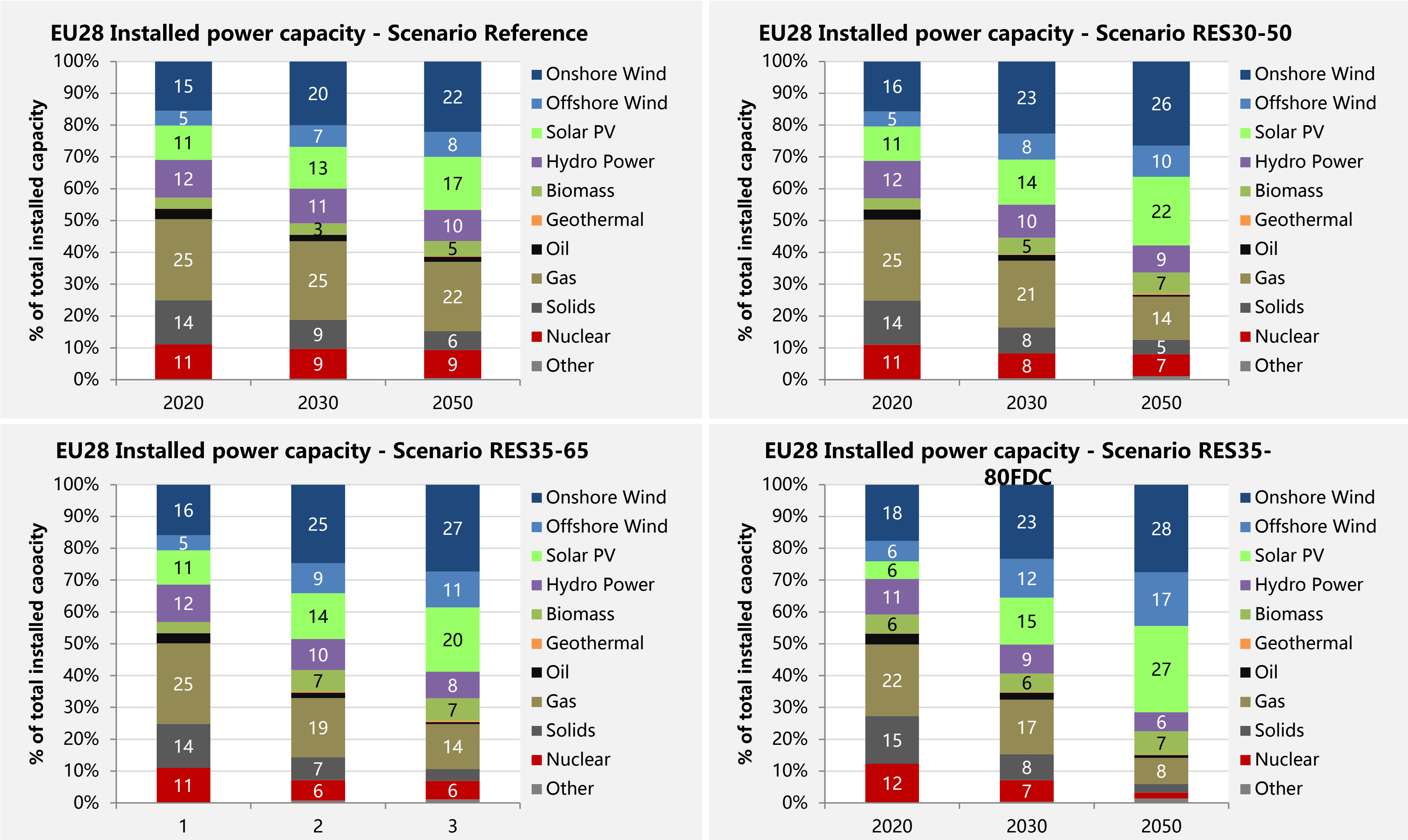
reasons; first, the assumed decarbonization targets of these scenarios result in a shift of demand towards electricity, as there are generally more options (from the perspective of available technologies) for reducing CO_2 emissions in power generation than on the demand side. Therefore, it is possible that decarbonization comes together with an increase in electricity consumption. Particularly in these scenarios, demand for electricity increases relative to the reference scenario by app. 10% at the EU28 level. This also explains the increase in investments in baseload capacity in the RES30-50 scenario compared to the Reference scenario. A second reason for observing increasing investment requirements with increasing RES penetration is that investments in variable RES (as it has already been explained) require support investments in flexible capacities. This becomes obvious when comparing the results of the RES35-65 scenario to those of RES30-50, where the increase in the RES target has resulted in an increase of peak devices and CCGT capacities. Finally, as the load factor of RES is (relatively) low, in scenarios with high RES penetration the overall level of capacity has to be higher to cover the demand. This is particularly obvious in the case of RES35-80FDC scenario.

Figure 9: Cumulative investments in the period 2020-2050 in the EU28, by type of plants



	Reference	RES30-50	RES35-65	RES35-80FDC
Other dispatchable RES	64	99	104	148
Hydro	16	22	24	29
Variable RES	808	1173	1237	1981
Flexible capacities	129	62	74	130
CCGT	167	67	81	47
Baseload	261	292	262	95

Figure 10: EU28 installed power capacity



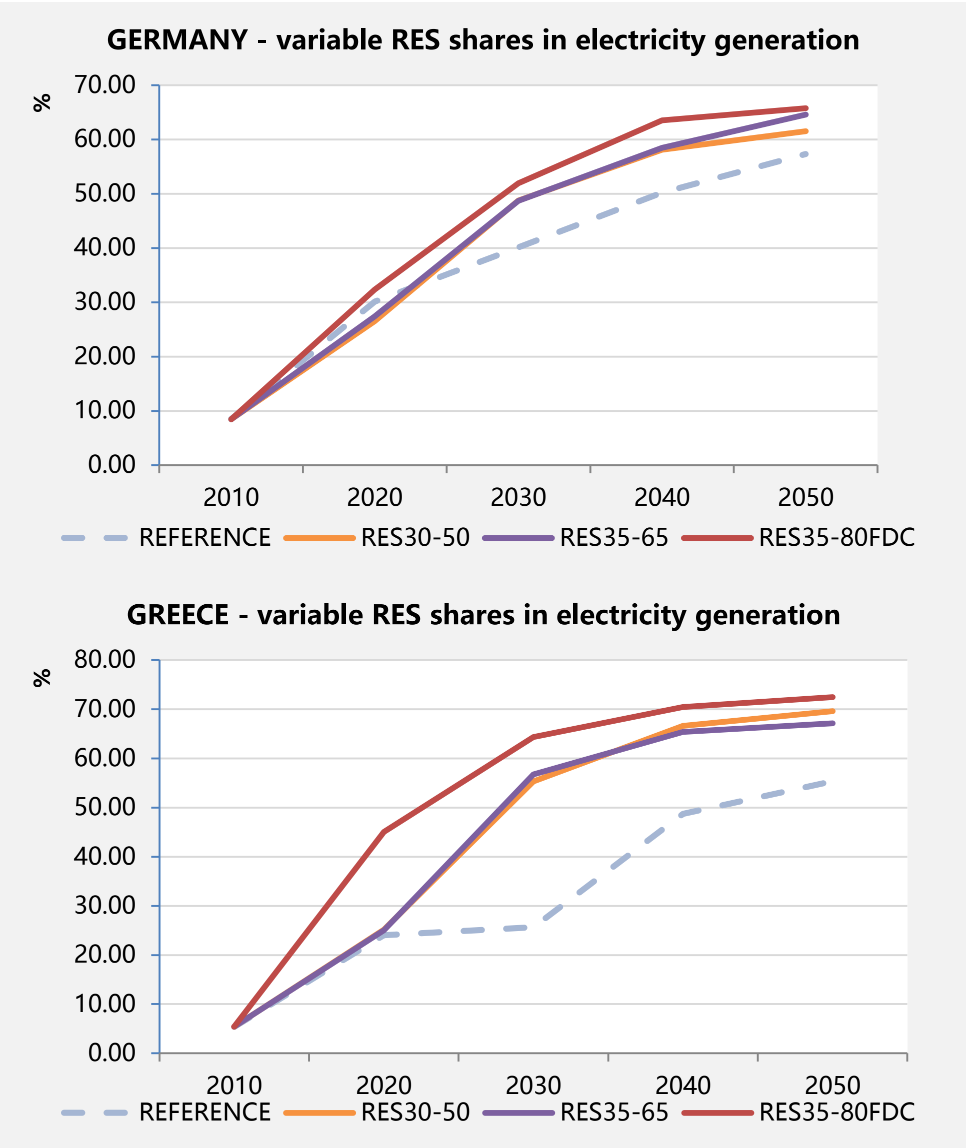
Source: PRIMES

Blocks with no labels for values less than 5%

4.2. The Greek and German power systems with high RES development

When looking at the Greek and German power systems from the perspective of decarbonisation, there appear to be some common characteristics. Both countries have limited options to develop "clean" base load capacities in the long term, due to no nuclear (Germany is phasing out nuclear capacities since 2025) and to the limited potential to implement CCS in coal/lignite capacities, especially in Greece. Therefore, decarbonisation of their energy systems implies very high shares of RES. Indeed, already in the RES30-50 scenario, the most modest scenario in terms of RES penetration considered in the analysis, the share of RES in power generation is very high in both countries, reaching 80% in 2050 in Germany and 95% in Greece. The respective figures for variable RES (wind and solar) is 62% for Germany and 70% in Greece. These figures increase (though not substantially) in the other two scenarios RES35-65 and RES35-80FDC, with Germany achieving 66% and Greece 72% in 2050 in the extreme RES35-80FDC scenario.

Figure 11: Shares of variable RES in electricity generation in Germany and Greece



The following figures show the cumulative investments in the period 2020-2050 in Greece and Germany in the scenarios of the analysis. In Germany, we observe a decrease in the overall level of investments for RES in the scenario RES35-65 compared to RES30-50. Although this result might seem counter-intuitive, in reality it is indicative of the re-allocation of RES across EU regions because of the assumed developments of the DC grid. This result demonstrates already at this point of the analysis that an enhancement of the interconnected system allows for sharing of resources and allows to achieve high shares of RES in the EU more effectively. In particular in the RES35-65 scenario, there is a shift of wind capacity development (including those of Germany) towards countries of the North Sea (mainly offshore wind) and the UK (offshore and onshore wind), with high wind speeds and increased potentials for electricity generation from wind. On the other hand, Germany appears to increase the level of investments in flexible capacities and to increase outflows of electricity during peak load hours.

Similar results cannot be observed for Greece when comparing the RES30-50 and RES35-65 scenarios, as the DC grid development assumed in RES35-65 does not involve the region of Greece, at least not directly. In RES35-65 scenario, Greece increases its share of variable RES capacities, both wind and solar, and it develops more hydro capacities. It also considerably increases the investments on thermal peak capacities while eliminating investments on CCGT units which serve mainly during medium load hours. Because of the limited potential of Greece to share balancing and flexibility services with other EU countries it should maintain large balancing/flexibility capacities at a national level.

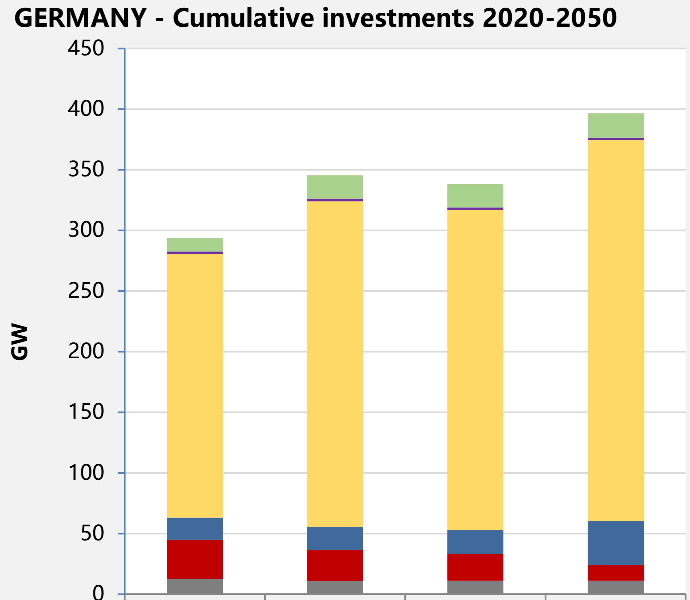
When examining the results of the RES35-80FDC scenario the picture is quite different, especially for Greece. This scenario assumes a full scale development of a DC grid network in the EU, including a connection between Greece and Germany through the Balkan region. In this scenario, the development of RES capacities in the North Sea countries is very significant and they contribute considerably to the achievement of the high RES EU targets of the scenario, as the extended topology of the DC grid allows for the diffusion of RES power in many countries. Germany benefits directly from the northern DC grid developments, as in scenario RES35-65. The scenario also assumes a linkage between Greece and Germany through the Balkan region, which allows the Greek power system to be integrated at a higher level to the EU grid and to participate more effectively in the sharing of resources compared to the RES35-65 scenario[4].

In particular this scenario shows less wind development for Germany relative to the RES30-50 and RES35-65 scenario, and more Solar PV development (Figure 11). This result in combination with the observations of scenario RES35-65 establishes a trend for Germany; RES capacities shift towards less wind and more solar PV as the DC grid network develops. Germany also appears to decrease investments in CCGT and baseload capacities and thus considerably increases the level of net imports during baseload hours, while on the other hand it develops more flexible thermal capacities and becomes a net exporter of electricity during medium and peak load hours.

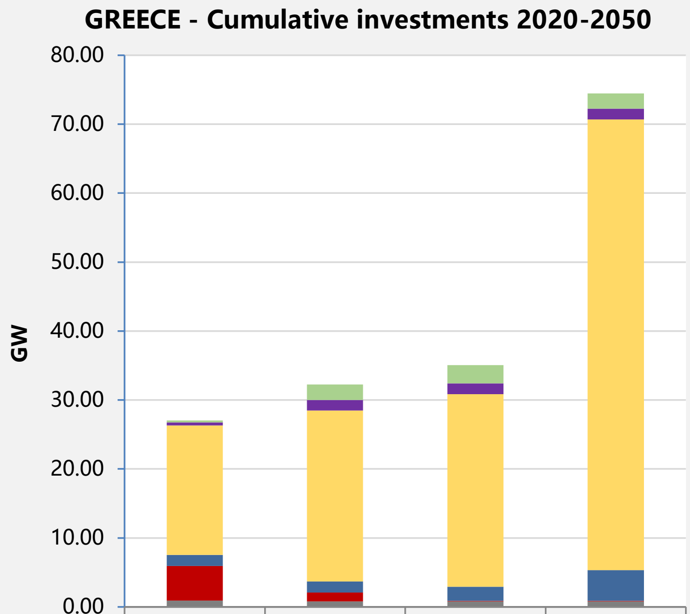
For Greece, the RES35-80FDC scenario is a scenario of very high Solar PV development. In this scenario, the linking of Greece to the rest of the EU through the Balkan region renders Greece a net exporter of electricity (Solar PV flows) to neighboring countries and through them to the rest of the EU. It thus plays a significant role in meeting the pan-EU high target of 80% RES in 2050. Compared to the RES35-65 scenario, it maintains the same level of baseload investments, as basically the additional RES serve to export electricity than meeting in country electricity requirements. The linkage allows for importing flows for flexibility purposes however some additional development of flexible capacities is observed, which is expected considering the very high level of Solar PV in the system.

[4] Note that this linkage is the interconnection introduced also in the sensitivity scenarios RES30-50_B and RES35-65_B which are to be analysed in the following chapter.

Figure 12: Cumulative investments in the period 2020-2050 in Germany, by type of plants

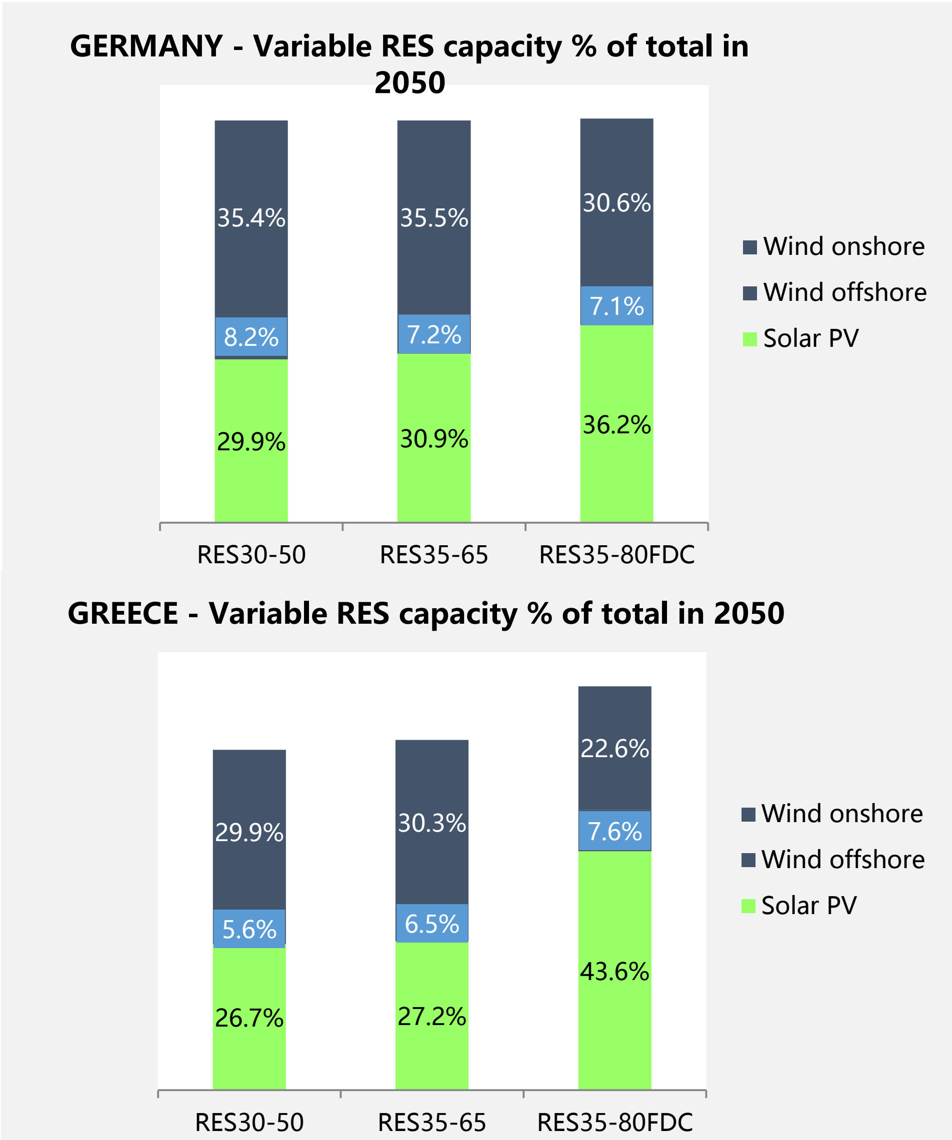


	Reference	RES30-50	RES35-65	RES35-80FDC
Other RES	11	19	19	20
Hydro reservoir	2	2	2	2
Variable RES	217	268	264	314
Flexible capacities	18	19	20	36
CCGT and CCS gas	32	25	22	13
Baseload	13	11	11	11



	Reference	RES30-50	RES35-65	RES35-80FDC
Other RES	0.31	2.24	2.67	2.22
Hydro reservoir	0.44	1.54	1.54	1.58
Variable RES	18.76	24.80	27.92	65.35
Flexible capacities	1.60	1.60	2.04	4.43
CCGT and CCS gas	5.05	1.26	0.08	0.08
Baseload	0.91	0.81	0.81	0.81

Figure 13: Installed capacity of variable RES as % of total installed capacity in 2050 in Germany and Greece



4.3. Impacts from interconnecting Greece-Germany

The results of the scenarios RES30-50, RES35-65 and RES35-80FDC discussed in the previous paragraph have already demonstrated that an enhanced interconnected power system in the EU allows for more effective allocation of RES across the EU regions and allows to share balancing and flexibility services instead of developing them mostly for in-country utilisation. In the scenario of very high RES penetration (RES35-80FDC) until 2050, the linkage has been proven very beneficial especially for Greece, as its geographic location renders it relatively isolated compared to other regions in Europe and does not allow for the diffusion of increased RES flows that result from the development of the DC grid network in the northern part of Europe. The sensitivity scenarios RES30-50_B and RES35-65_B examine the impact of the introduced linkage between Greece and Germany, isolated from the rest of the DC grid development assumed in the base scenarios.

Table 5 summarizes the interconnection assumed in the sensitivity scenarios analysed with the PRIMES model (more details provided in paragraph 3); a total of 10GW is introduced connecting Greece and Germany passing through countries of the Balkan region and allowing access to the flows also in the intermediate countries.

Table 5: DC lines introduced for analysis of sensitivity scenarios RES30-50_B and RES35-65_B

Line 1: 4GW	Greece >FYROM > Serbia > Hungary > Austria > Germany
Line 2: 6GW	Greece >Bulgaria > Romania > Hungary > Slovakia > Czech Republic >Germany

The utilization of the interconnections introduced is very high; in the scenario RES30-50_B the load factor on the lines is on average app. 0.8 while in the scenario RES35-65_B the load factor becomes close to 1 in most instances. This result by itself demonstrates a bottleneck on the current state of the network, as it appears that the introduction of such a linkage unlocks a considerable amount of flows.

Figure 14: Installed capacity of variable RES and flexible capacities as % of total installed capacity in the scenarios with (_B) and without the interconnection between Greece and Germany

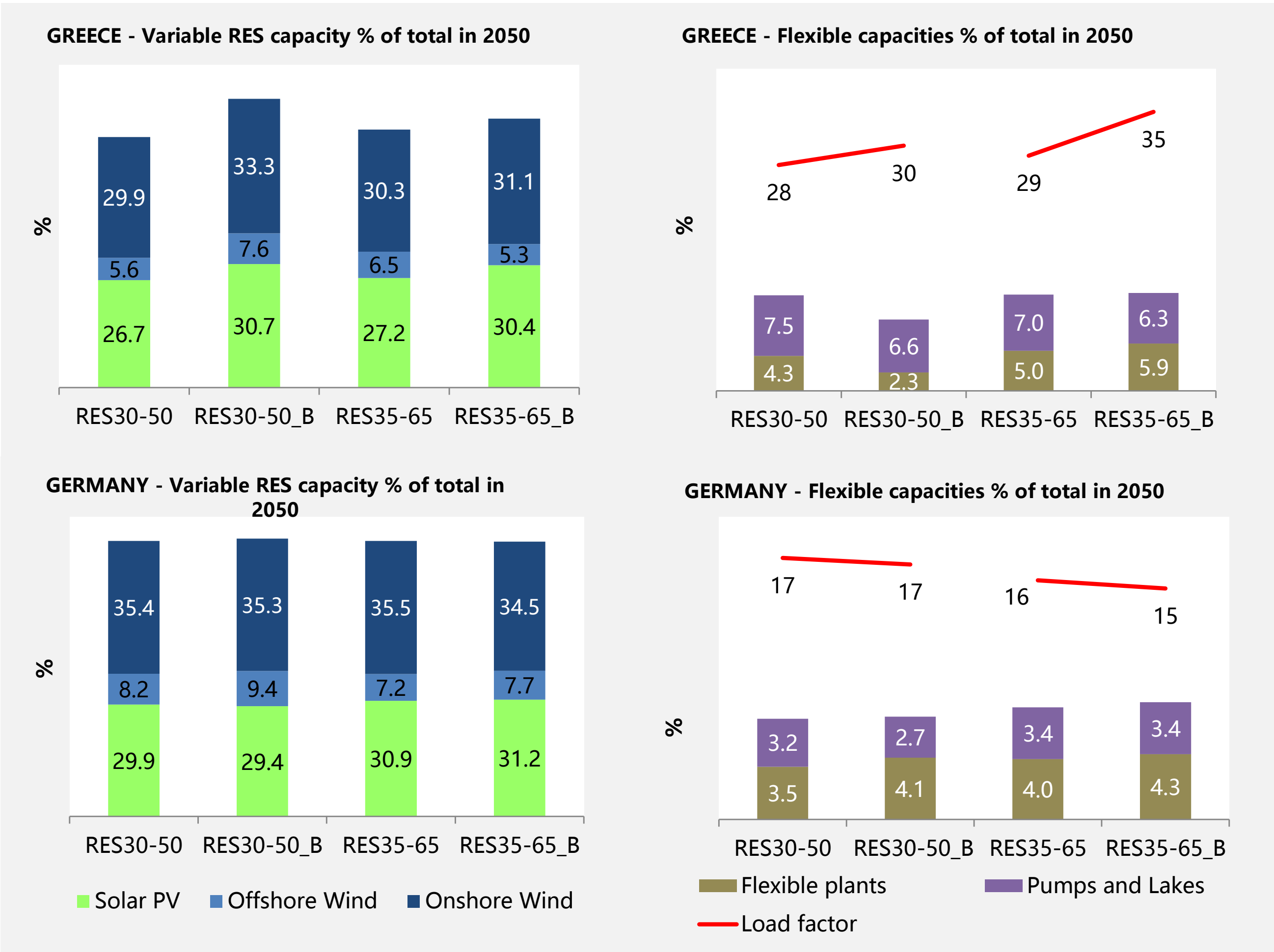
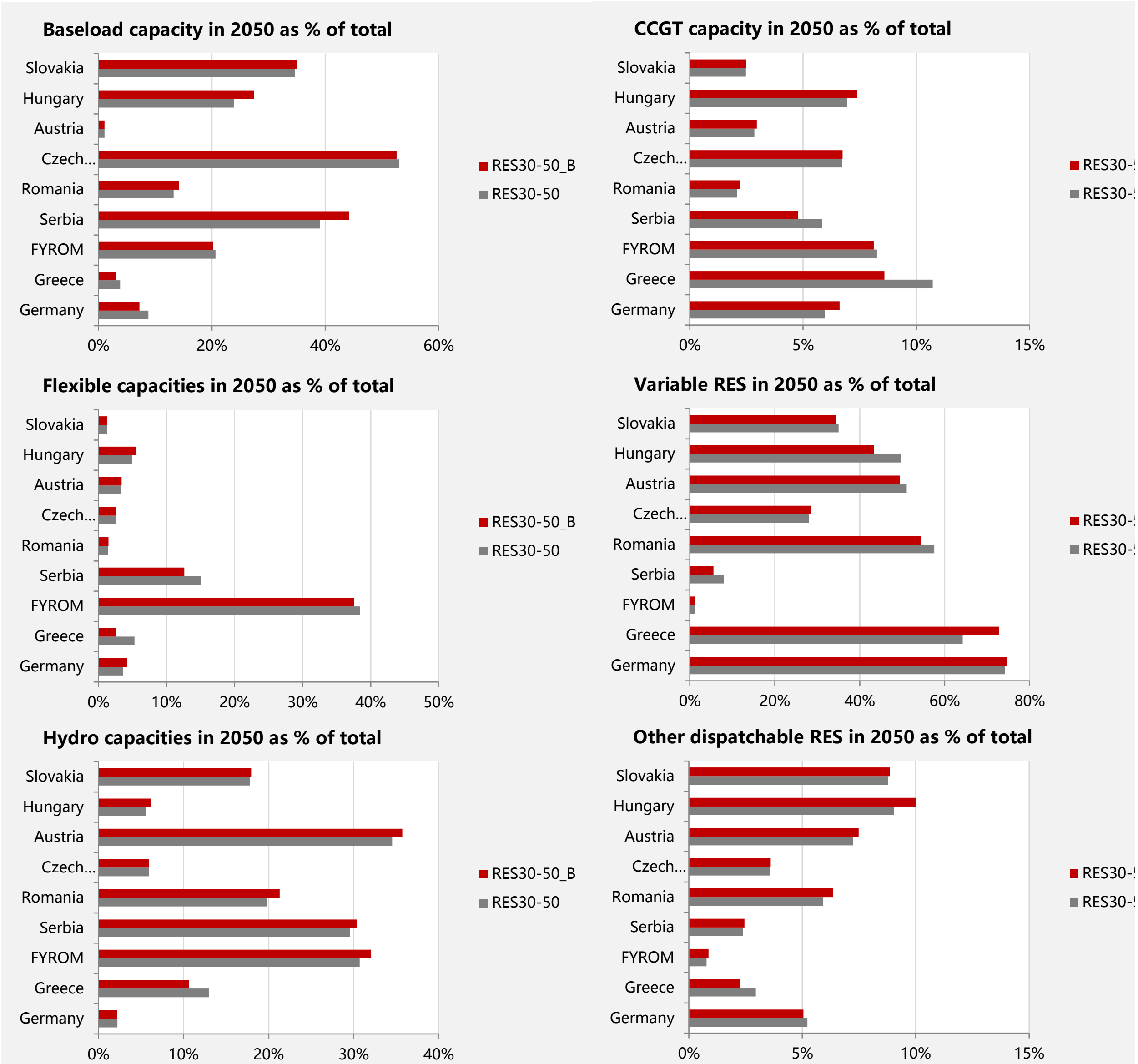


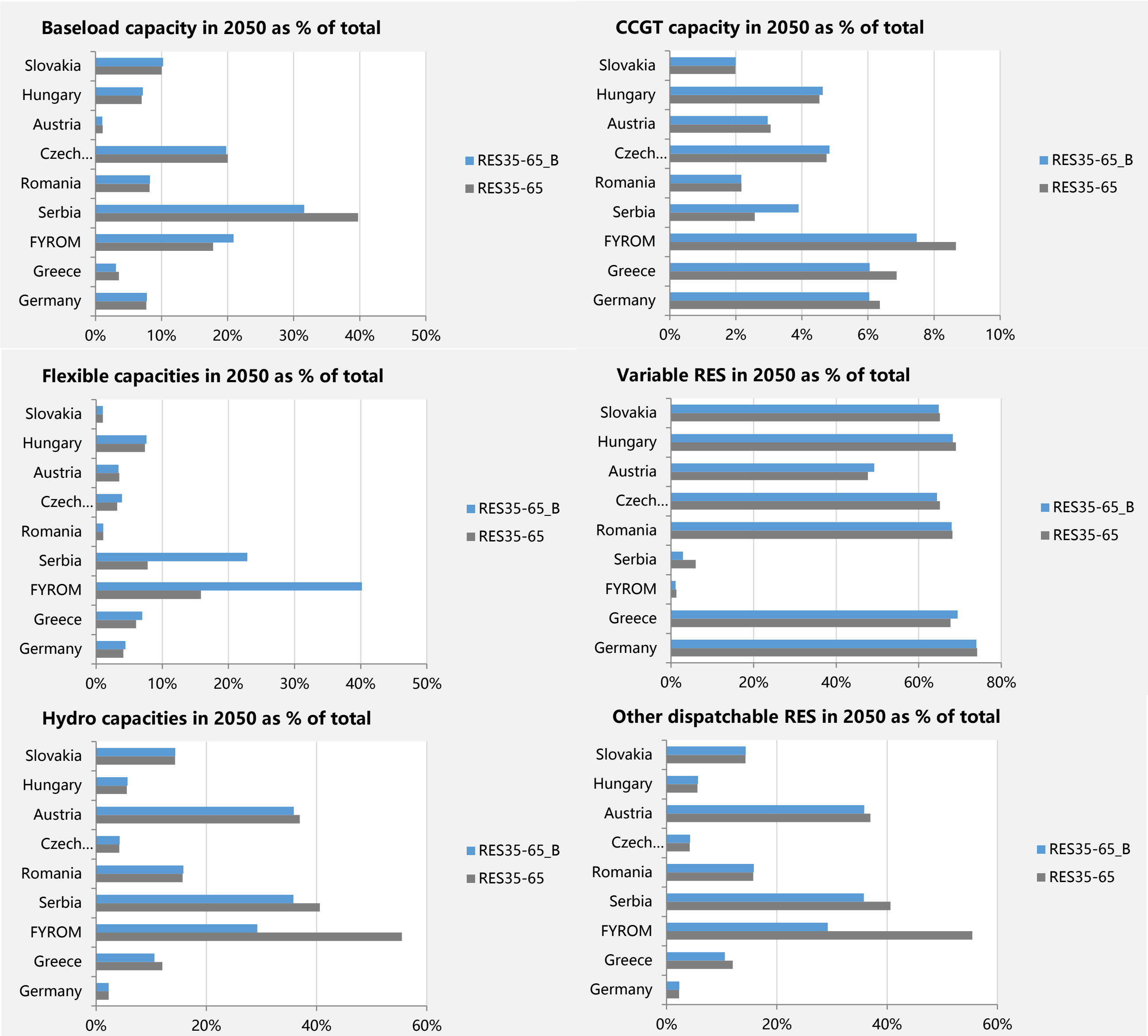
Figure 15: Structure of electricity generation in 2050 along the countries of the interconnection between Greece and Germany assumed in the scenario RES30-50_B – Comparison of scenarios RES30-50 and RES30-50_B



The left side of Figure 14 demonstrates the impact of the interconnection on variable RES developments. For Greece, it allows for higher developments of variable RES, mainly for solar PV but also for wind onshore and offshore capacities. For Germany, the impact is less pronounced on the overall level of variable RES capacities. In scenario RES30-50 (no DC grid developments in rest of the EU) the interconnection results in an increase of wind (mainly offshore) capacities. In the scenario RES35-65 which includes some DC network developments which connect the German system to regions with high potential of wind generation, the interconnection results in some additional investments in Solar PV.

We see therefore that in terms of renewables, the interconnection unlocks a significant potential of flows of solar PV (mainly) and wind generation from Greece to neighboring countries, revealing a bottleneck of the current state of the network. For Germany as well, the interconnection allows for

Figure 16: Structure of electricity generation in 2050 along the countries of the interconnection between Greece and Germany assumed in the scenario RES35-65_B – Comparison of scenarios RES35-65 and RES35-65_B



increased outflows of RES generation to neighboring countries, with the difference that Germany is better embedded in the EU network and is therefore affected less. The size of the German power market compared to the Greek power market is also a defining factor to the observed results.

The redistribution of RES capacities due to the interconnection comes along with a redistribution of flexible capacities. Looking at the results for Greece (Figure 14) we see that in scenario RES30-50_B Greece has lower requirements for in-country flexible capacities despite the significant increase of RES. It obviously benefits in terms of flexibility services from the interconnection, importing flows to cover for such requirements. Importing flows during medium and peak load hours come from FYROM and Serbia. Greece increases its imports also from Bulgaria in this scenario, indicating a propagation of the impact of the interconnector to a wider region than that of the countries directly linked to it, and a redistribution of flows collectively in the EU. In scenario RES35-65_B the picture changes for Greece. Redistribution of flows in Europe due to the development of the DC grid (which affects mainly the northern part of Europe) results in somewhat higher requirements of flexible capacities in Greece; notice however that their utilization is very high in particular for this scenario (right side of Figure 14), as Greece increases also the outflows of medium and peak load capacity. Therefore, in the case of the RES35-65 scenario, the interconnection results in higher developments of not only RES but also of flexible capacities in Greece. Outflows of medium and peak load capacity to FYROM and Bulgaria increase considerably with the introduction of the interconnector.

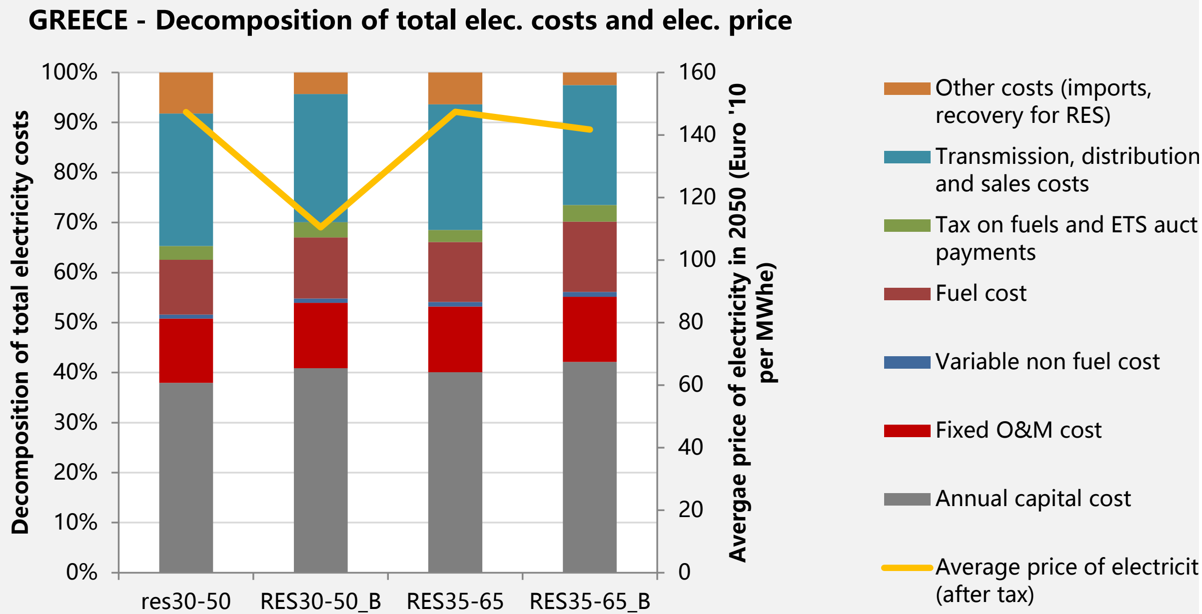
Looking at baseload capacity and flows in Greece (Figure 15 and Figure 16), the impact of the interconnection is a decrease of baseload developments and subsequently an increase in importing flows, in both RES30-50_B and RES35-65_B scenarios. The results of the analysis show that with the interconnection more baseload capacities develop in the countries of the Balkan region and diffuse baseload flows to Greece and other neighboring EU countries.

Looking at the results for Germany in terms of flexible capacities, impacts from the interconnection are – as for variable RES – less pronounced compared to the results for Greece. In both scenarios Germany appears to develop slightly more flexible capacities and to increase such outflows. Baseload capacity developments on the other hand decrease with the introduction of the interconnector, in both scenarios.

The additional interconnection of the RES30-50_B and RES35-65_B sensitivity scenarios has implications on security of supply of the countries involved, with security of supply indicators improving according to the results of the analysis. In particular, the reserve margin indicator (i.e. the ability of the system to meet peak load capacity, calculated as the sum of installed capacity considering its average annual availability plus the potential of import flows over the annual peak load) of both Greece and Germany improves, with the improvement being more pronounced for Greece than for Germany. As expected, improvements of the reserve margin indicator are observed for all countries that lie along the new interconnection. Moreover, when looking at the EU as a whole, the reserve margin indicator appears to improve by 2 percentage points in the RES30-50 scenario and by 0.2 percentage points in the RES35-65 scenario having lower overall impact owing to the extended grid developments that are assumed in this scenario.

Summing up the impacts of the interconnection discussed so far, it allows for more efficient allocation of RES developments among countries facilitating the achievement of high RES shares, it allows for sharing of system resources for flexibility purposes, and it brings benefits in terms of security of supply. These benefits also translate to savings on system electricity costs and hence lower electricity prices (net of the cost of interconnection which will be discussed in the following chapter). The impacts on costs and prices is more pronounced for Greece than for Germany; Greek electricity prices reduce 4% to 20% with the interconnection, stemming mainly from a significant reduction of import costs (Figure 17), while for Germany the electricity price maintains the same level with and without the interconnection. Benefits in terms of cost however appear also for the countries that lie along the route of the interconnection, who appear to have 2-3% lower electricity prices due to the interconnection. But also other countries of the EU enjoy benefits in terms of cost due to the interconnection; on average in the EU electricity prices appear to be 1-2% lower in the scenarios with the interconnection than in the scenarios without the interconnection. It appears therefore that there are spill-over effects to the whole of the EU with this particular enhancement of the energy system and that countries that are not directly linked to the interconnector are however receiving benefits for the operation of their energy system, an effect which is known in the literature as “free riding”. The benefits in terms of cost for the EU are lower in the RES35-65_B scenario which assumes a medium scale development of the DC grid network relative to the RES30-50_B, which does not include this assumption

Figure 17: Decomposition of total electricity costs and average electricity price of the period 2020-2050 for Greece and Germany in the scenarios with (_B) and without the interconnection between Greece and Germany



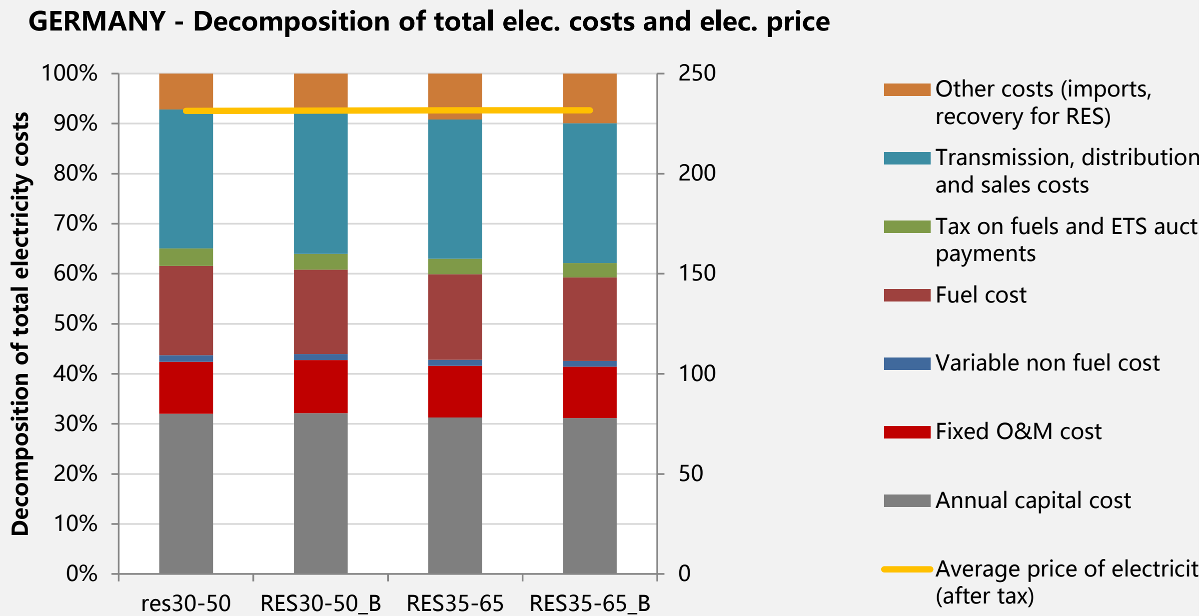
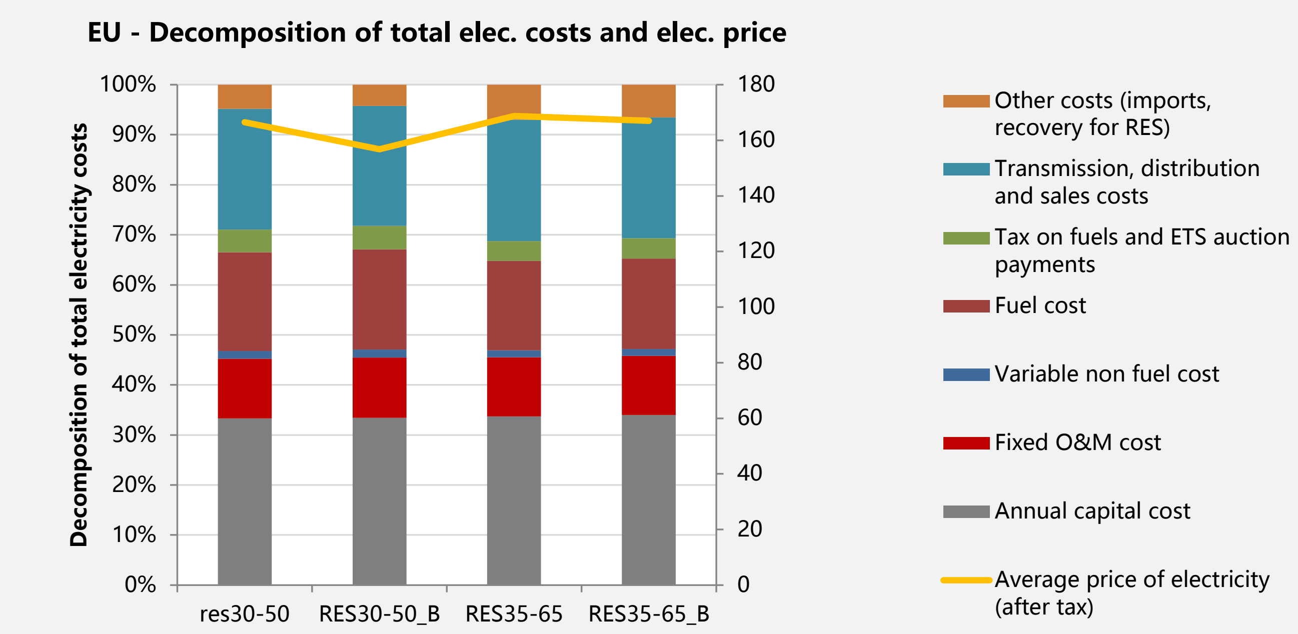
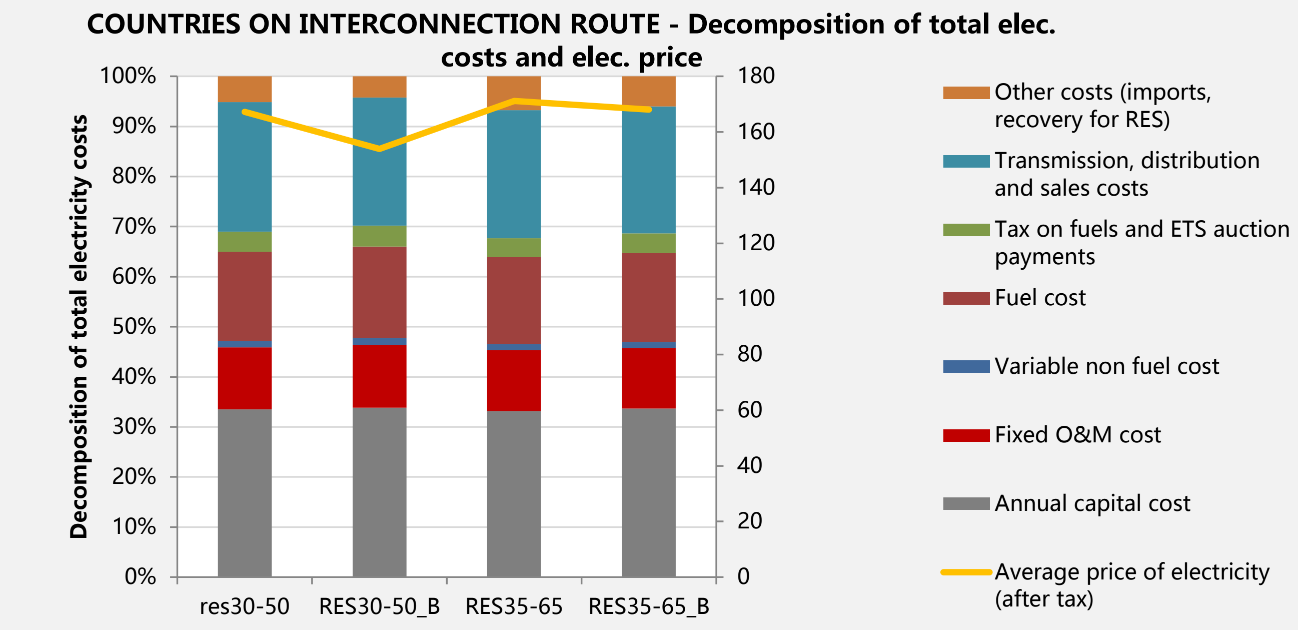


Figure 18: Decomposition of total electricity costs and average electricity price of the period 2020-2050 for the EU members states and the countries that lie along the route of the interconnection between Greece and Germany in the scenarios with (_B) and without this interconnection





Results of the enhanced PRIMES model

The results of the analysis with the PRIMES model on the impacts of interconnecting Greece and Germany have been further assessed with the enhanced version of the model, which has increased time resolution and captures in higher detail the fluctuations of variable RES, as well as of power demand. This part of the report takes a closer look on the impacts of the interconnector on the flows of Greece and Germany, and it also makes a comparison of the results of the two versions of the model in regard to flexibility requirements of the power systems of Greece and Germany in a high RES context.

Figure 19 and Figure 20 depict the impact on flows for Greece and Germany in 2050 (for representative time segments of spring[5]). The figures show very clearly that the introduction of the interconnection results in increased variability of trade flows especially during the time segments with increased generation of variable renewables. The figures also show a complementary effect between Greece and Germany; at the time segments that Greece appears to increase exports, Germany appears to increase imports. Impact on trade flows for both countries seem to follow more closely the development of solar PV, i.e., at times with strong solar both countries appear to have higher outflows and hence to decrease their net imports.

Looking at the results for Greece (Figure 19), apart from significantly higher level of exports at the times with high generation of variable renewables, Greece appears to change the utilization pattern of hydro reservoir (lakes) capacities. While in scenario RES30-50 hydro reservoir capacities appear to be dispatched at times when the system has high ramping requirements (hours that solar PV generation decreases) in scenario RES30-50_B they appear to be dispatched also at times of high generation from RES, and in particular at times of peak load; this implies that in this scenario the interconnection allows for exporting of not only variable RES flows but also of dispatchable hydro flows. This also implies that the system's flexibility requirements are no longer met through hydro reservoirs (as appears for scenario RS30-50), but through importing electricity; it has already been discussed in the previous chapter that the interconnection in scenario RES30-50_B allows Greece to benefit in terms of flexibility, importing flows at times when the system has high flexibility requirements. Hydro reservoirs serve more as peaking capacities rather than flexible capacities in this scenario. The results for scenario RES35-65_B for Greece are not similar in respect to the deployment of hydro reservoir capacities, however, also in this scenario the increase of outflows at the hours of variable RES generation is very significant.

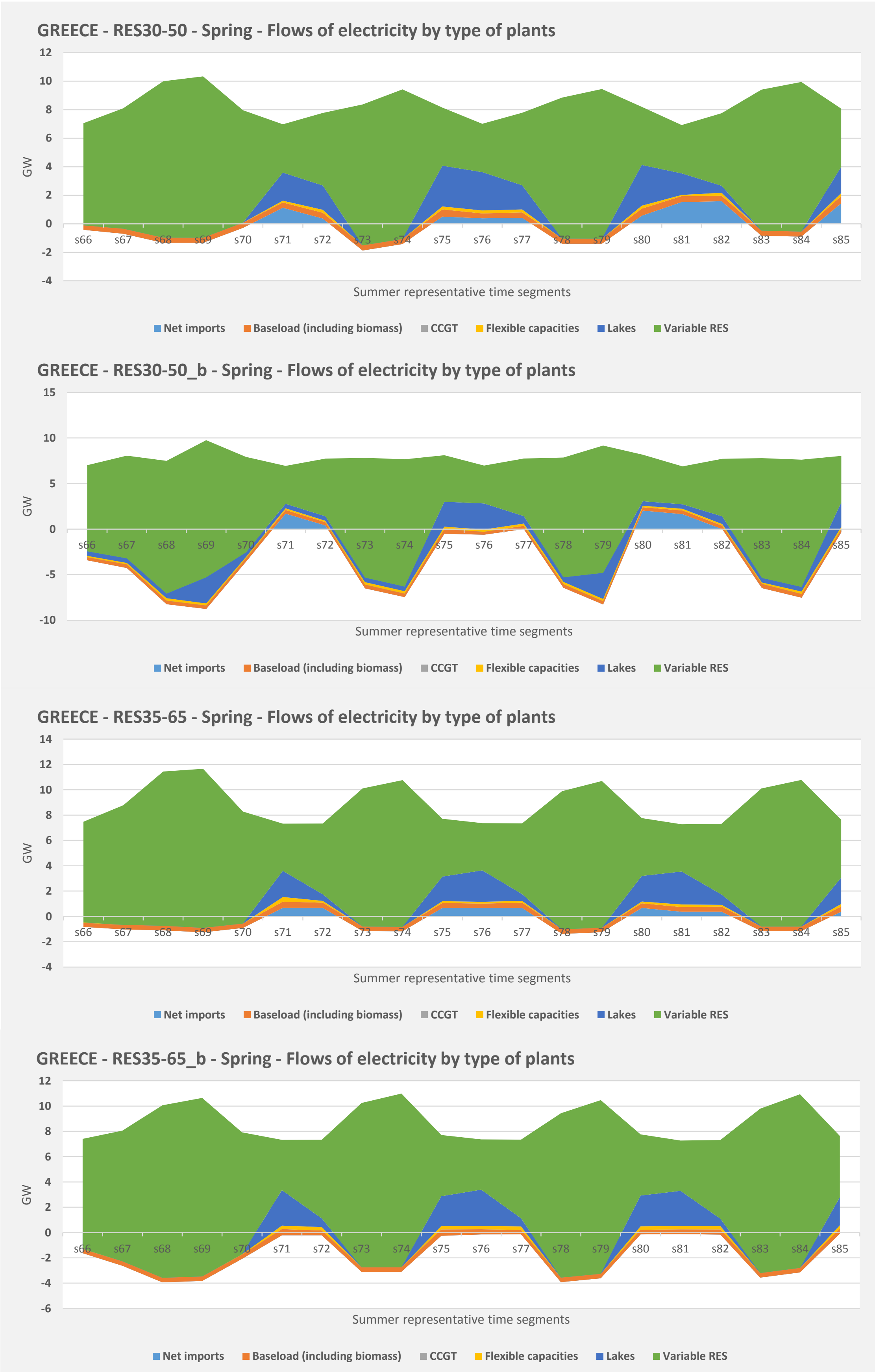
Looking at the results for Germany (Figure 20) for scenario RES30-50_B compared to scenario RES30-50, the interconnection between Greece and Germany results in higher net imports during times of weak variable RES and lower (negative) net imports at times of strong variable RES. The effects are less pronounced for Germany than those observed for Greece, as Germany is better interconnected to the EU network due to its topology and also because the size of the German market is much higher and is therefore less affected by the additional flows from the interconnection. Comparing the results for scenarios RES35-65_B and RES35-65 for Germany the differences in the flow patterns are small; it is reminded that this set of scenarios assumes medium scale development of the DC grid network which affects the developments in the German power system very considerably and delimits the impact of the interconnection with Greece.

In order to obtain further indication of the relationship between trade flows, variable RES and the interconnections of Greece and Germany, we calculated the correlation of net import flows and variable RES generation for the scenarios of the analysis. In particular, we calculate the change in net imports and the change in variable renewable generation for every time segment between scenarios

[5] For an explanation of the derivation of time segments see chapter 2.1, paragraph "Modelling of variable RES". Figures 15 and 16 do not show the duration of each time segment.

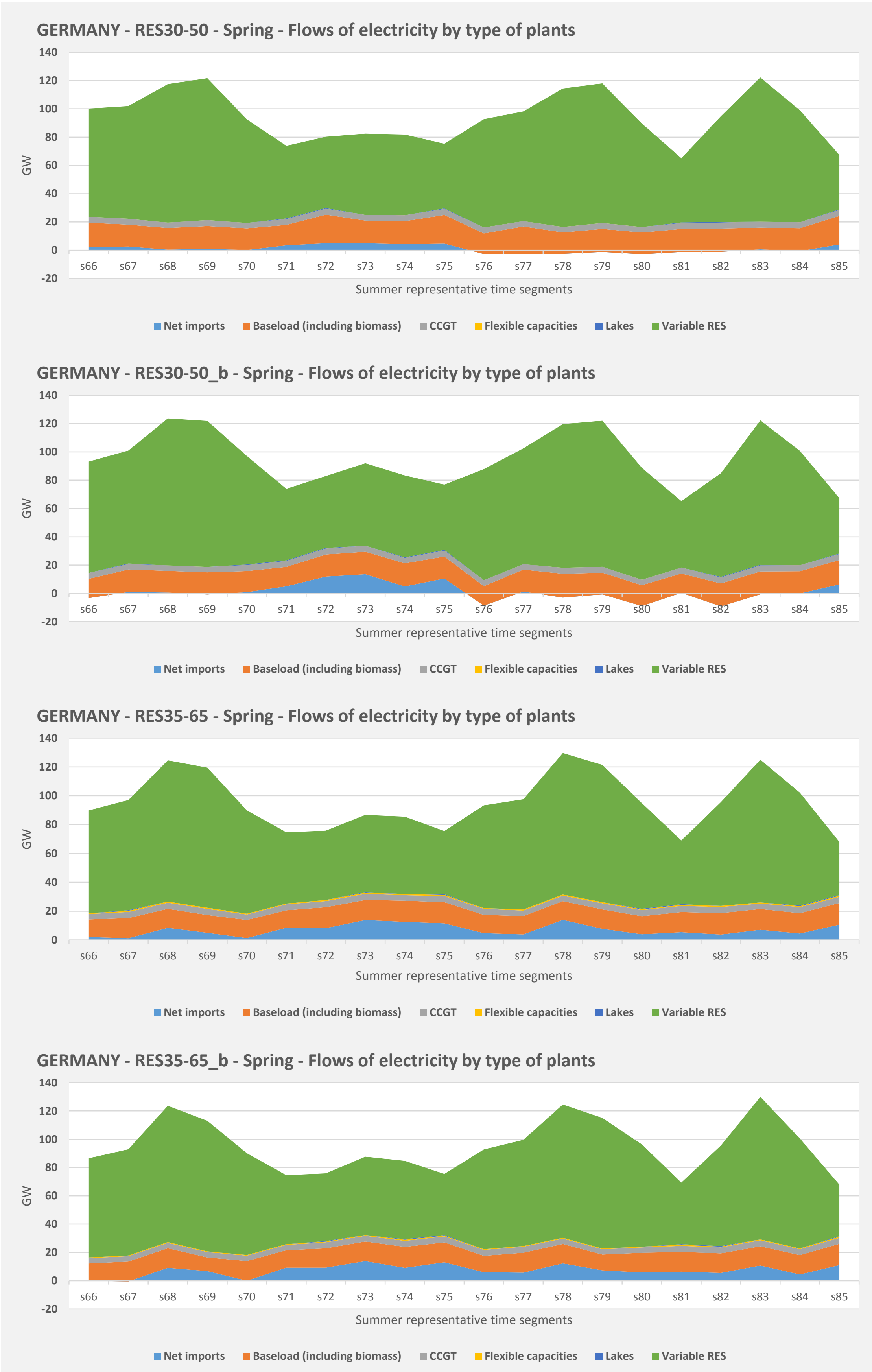
RES30-50_B - RES30-50 and RES35-65_B – RES35-65 and calculate the correlation of these changes (Table 6).

Figure 19: Flows of electricity by plant type in Greece in 2050 in the scenarios with (_B) and without the interconnection between Greece and Germany, for representative time segments of spring[5]



time segments	s66 - s70	s71 - s75	s76 - s80	s81 - s85	time segments	s66 - s70	s71 - s75	s76 - s80	s81 - s85
Greece	weak sun	strong sun	strong sun	strong sun	Germany	weak sun	weak sun	weak sun	strong sun
	strong wind	weak wind	weak wind	weak wind		strong wind	weak wind	strong wind	weak wind

Figure 20: Flows of electricity by plant type in Germany in 2050 in the scenarios with (_B) and without the interconnection between Greece and Germany, for representative time segments of spring[5]



time segments	s66 - s70	s71 - s75	s76 - s80	s81 - s85	time segments	s66 - s70	s71 - s75	s76 - s80	s81 - s85
Greece	weak sun	strong sun	strong sun	strong sun	Germany	weak sun	weak sun	weak sun	strong sun
	strong wind	weak wind	weak wind	weak wind		strong wind	weak wind	strong wind	weak wind

Table 6: Correlation between the change of net imports and the change in variable renewables generation due to the interconnection Greece -Germany (using the flows of year 2050)

Correlation of the impact of the interconnection on net imports and on variable renewables	Greece	Germany
Scenario RES30-50_B	-0.67	-0.22
Scenario RES35-65_B	-0.71	0.01

The results show for Greece a significant negative correlation of the impact of the interconnection on trade flows and on variable RES generation, implying that in every time segment the increase in variable RES generation in scenarios RES30-50_B and scenarios RES35-65_B relative to scenarios RES35-50 and RES35-65 respectively can be associated with a corresponding decrease in net imports. The results for Germany reveal a weak to non-existent (scenario RES35-65_B) relationship between net import changes and variable RES changes. This result (as it has already been discussed) is due to the higher level of interconnections of Germany to the rest of the EU network, especially in scenario RES35-65_B, which assumes medium scale development of DC grid in the EU that creates more connections of Germany to the countries of the North Sea. The impact of the interconnection with Greece is very small relative to the changes brought to the German system from the interconnection with the countries of the North Sea.

Table 7 summarizes the differences on scenario results between the enhanced PRIMES model (with 120 time segments) relative to the standard version (11 time segments). As expected the impacts regard mainly flexible capacities, as the enhanced version captures better the fluctuation of variable renewables and demand, and consequently the power system requirements for flexibility and balancing services. The size of the differences is not high enough to alter the conclusions derived from the analysis with the standard version of PRIMES. Overall, the employment of the enhanced version of the model allows to demonstrate that the operation of a system with very high RES as projected with the standard version of PRIMES is feasible.

Table 7: Comparison of the output of the enhanced PRIMES model relative to the standard version on investments induced by the Greece-Germany interconnection

Impact of the interconnection on investments - Output of the enhanced PRIMES model relative to the standard PRIMES version				
	Scenario RES30-50_B		Scenario RES35-65_B	
	Greece	Germany	Greece	Germany
Baseload	very similar results	very similar results	very similar results	very similar results
CCGT	very similar results	very similar results	very similar results	additional CCGT capacities
Flexible capacities	lower benefits of the interconnection in terms of flexible capacities	lower benefits of the interconnection in terms of flexible capacities	higher benefits of the interconnection in terms of flexible capacities	higher benefits of the interconnection in terms of flexible capacities
Hydro	higher development of small hydro plants	very similar results	higher development of small hydro plants	very similar results

4.4. Assessment of the economic viability of the interconnection between Greece-Germany

The analysis in chapter 4.3 has shown the impacts on the national power systems of Greece and Germany from the introduced interconnection; it remains to discuss its economic viability. The assessment is based on determination of the tariff for using the interconnector that breakeven cost. As method, benchmark internal rate of return (IRR) is used. As grid infrastructure is subject to regulation as a natural monopoly, with grid investments involving low risk, we have set the rate of return benchmark to 6%. Such values of the rate of return are proposed for similar analyses in the literature; (see indicatively [11] and [12]).

The estimation of the cost of the interconnectors takes into account estimations of the costs of the components, including inland DC cables, convertors and costs depending on length and geographical shape. Total investment cost has been estimated approximately at 40bn€. The assumptions regarding the implementation of the project are the following:

- Beginning of the project: 2025
- Every 5 years 1/6 of the project is delivered and paid for
- End of project lifetime: 50 years

Taking into account the projections of flows through the interconnectors the analysis calculates the present values of the revenues from the flows, discounted by the benchmark IRR of 6%. Following this approach the levelized tariff is estimated at **6 Euros/MWh** for both RES30-50_B and RES35-65_B scenarios.

Comparing to international unit transmission tariffs for merchant interconnectors, the obtained value of the tariff is reasonable and competitive for the RES-based trade. We may therefore conclude that there is basis for funding the implementation of such a project.

The economic viability of the Greece-Germany interconnection has also been examined for the very high RES scenario RES35-80FDC and it has been assessed as financially feasible also in this context, with the calculated tariff on the flows of the interconnectors that are required to achieve 6% rate of return being equal also in this case to 6 euros per MWh.

4.5. Conclusion

The analysis with the PRIMES model focuses on examining the impact of introducing an interconnection between Greece and Germany through the Balkan region and assessing its benefits for the power system of the two countries considering fully their embedment to the European interconnected system. The analysis shows that the introduction of the interconnector allows to harness the potential of Solar PV as well as wind onshore developments in Greece. The interconnection allows for a synergistic exploitation of the RES potential between the two countries, as it shows a tendency towards higher solar PV capacities in Greece in parallel to lower wind capacities in Germany. The results are affected to a significant level by the assumptions on the DC network developments in the rest of the EU which unlock flows of wind generation from the countries of the North Sea and affect to a wide extend the developments observed for Germany.

The interconnection allows for a redistribution of the balancing and flexible capacities among the countries that lie along the route of the interconnectors and also neighboring countries, improving their utilization. Power trade develops considerably, with the power lines being used at high rates and propagating benefits to other countries and at the EU-wide level. The interconnection brings also benefits in terms of security of supply, improving reserve margin indicators at national levels. The described benefits also translate to savings in terms of system costs, with electricity prices reducing on average for the countries that lie along the interconnection route around 2-3%. Other countries in the EU also benefit in terms of electricity prices (free riding effect) resulting on average to 1-2% lower prices with the introduction of the interconnection.

The analysis employed also an enhanced version of the PRIMES model specifically developed for the RESDEGREE project, with higher time resolution than the standard version of PRIMES. The enhanced version captures better the fluctuations of variable RES generation and of demand and allows to take a closer look on the impact of the interconnection on trade flows and on flexibility requirements. The simulations with the enhanced version demonstrate that the impact of the interconnection on flows is complementary for Greece and Germany, however impacts are more pronounced for Greece than for Germany. It shows that outflows of electricity are increased at times of high variable RES generation while inflows increase to fulfil flexibility. The employment of the enhanced version of the model allows to demonstrate that the operation of a system with very high RES as projected with the standard version of PRIMES is feasible.

Assuming that a desirable internal rate of return for such a project would be 6%, the estimated price that if applied to the flows of the interconnection would yield the desired level of the internal rate of return is 6 euros per MWh. Such a price is comparable to international unit transmission tariffs for merchant interconnectors, and therefore the project has been assessed as economically viable. Considering the described benefits for the energy systems of the countries involved it is worth considering its implementation.

For the benefits of the interconnectors to be demonstrated in reality, and for the interconnector to be indeed an economically feasible project, there are considerable preconditions. The analysis assumes that the markets that lie along the route of the interconnectors (Balkan region) are functioning properly and that there is wide market-coupling. Moreover, the analysis assumes the perfect functioning of the Internal Energy Market and flow-based allocation of interconnection capacities. In reality, there currently exist significant distortions (e.g. administratively allocation of interconnection capacities) which if they persist would eliminate the benefits of the proposed Germany-Greece interconnection. As a closing remark, it should be noted that the analysis is subject to model limitations. Market imperfections are not captured by the model; while the model captures adequately the interactions between the national energy systems, it is limited in regard to geographic and time resolution.

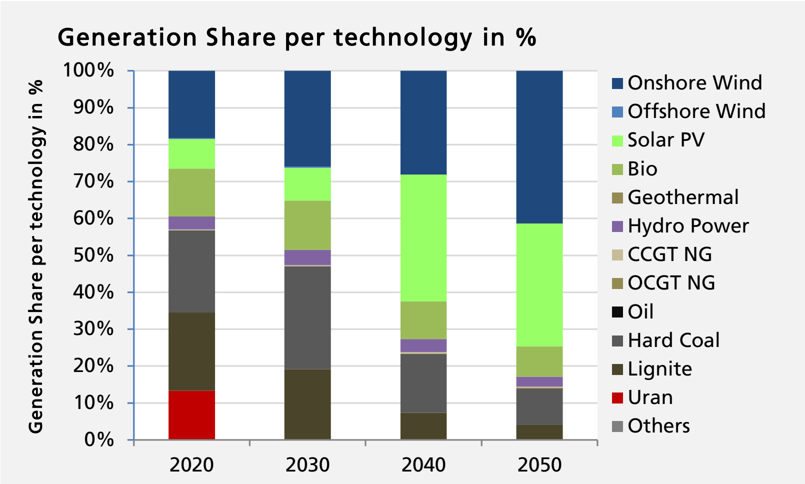
The results of the analysis have been used as inputs to the RESlion model which although it lacks the pan-EU perspective of PRIMES, it has higher regional and temporal resolution and hence allows to alleviate some of the above limitations. The analysis with RESlion described in the following chapter examines more in depth the issues that arise within the energy systems of every country.

5. Modelling results of the RESlion model

5.1. Generation portfolio in Germany

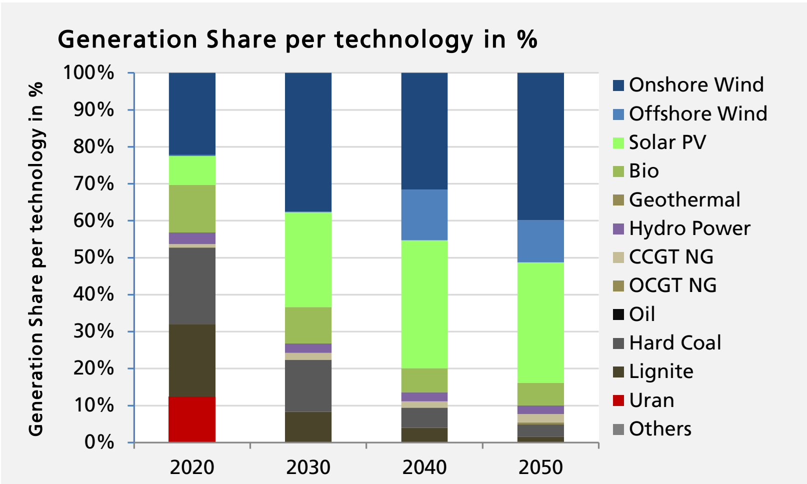
In all scenarios (see chapter 3), RES-E share in Germany ranges from 70% to 83% (results of the PRIMES modelling). Certainly, this small difference basically leads to similarities of the generation portfolio in the power system until 2050. However, the power systems in most of the neighbouring countries show stronger difference of RES-E share compared to the overall generation. This reflects the current national developments and targets of the other EU countries as their RES-E shares have not finally defined yet. However, these differences of potential European environment influence the generation portfolio in Germany when analysing the optimal solution obtained by RESlion. Therefore, it can be already concluded that the German generation portfolio optimally has to be adapted to the developments in the neighbouring countries.

Figure 21: Generation shares in RES35-65_B scenario (electricity demand in 2050: 678 TWh)



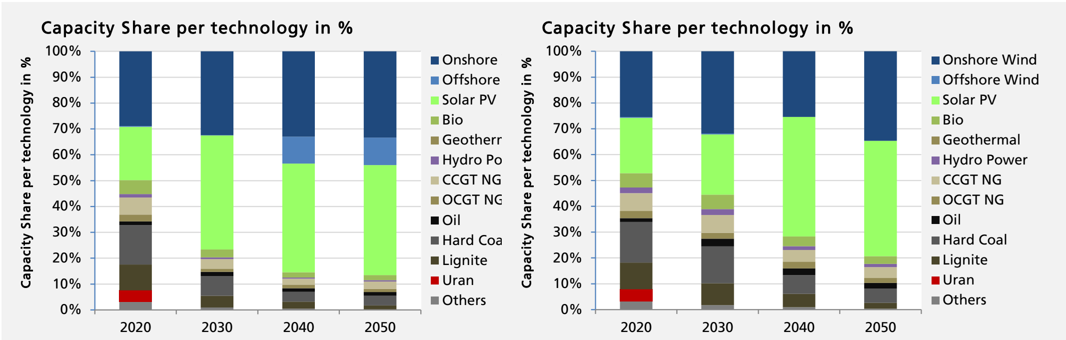
The analysis of the RESlion results is focused here on the differences between the RES35-65_B and RES35-80FDC scenarios for simplicity reasons (and the similarity of the RES-E share in the Germany system in all scenarios). As shown in Figure 21 and Figure 22, generation from onshore wind, offshore wind and PV have very remarkable shares on the overall electricity generation in Germany in year 2050 in both displayed scenarios (RES35-65_B and RES35-80FDC). The difference in both scenarios is mainly caused by an increase of the RES-E share in scenario RES35-80FDC. Nuclear phase out is linked with a strong decrease of brown coal and hard coal fired power plants. Biomass and gas turbines (as well as hard coal fired power plants in some scenarios) remain as important factors for flexible power generation.

Figure 22: Generation shares in RES35-80FDC scenario (electricity demand in 2050: 678 TWh)



In terms of installed capacities, both scenarios show a difference in terms of the split between renewables and conventional power plants as this is assumed as scenario input. However, when higher shares of renewables are reached, optimally offshore wind energy contributes to the targets; whereas at lower targets this technology option is not foreseen under cost minimization targets according to the RESlion model (see Figure 23). Due to lower full load hours of PV, installed capacity is the largest for this technology although most of the electricity is generated by onshore wind energy.

Figure 23: Capacity share per technology (left: RES35-65_B scenario, right RES35-80FDC scenario)



If the results in terms of installed capacity per technology are compared for both scenarios between PRIMES and RESlion the following conclusions can be developed. The differences are mainly caused by the regional approach in the RESlion model, by its linear cost-supply curves in contrast to the non-linear cost-supply curves of the PRIMES model, and the used assumptions which are used in both models for the overall environment of the European electricity system. Three important conclusions can be highlighted:

1) PV installations in Germany are higher in 2050 (RESlion results).
2) Coal power plants have a higher share in 2050 compared to CCGT power plants.
3) Offshore wind energy has a smaller impact in 2050.

All three aspects can be explained by the different model approaches. Certainly, regional distributed RES generation with interactions to neighbouring countries facilitates the integration of intermittent RES generation in the system. At the same time, less flexible generation is necessary as higher amount of RES are installed in Germany which leads to higher curtailment but also more exchange with neighbouring countries. If grid constraints in Germany are considered, it is clear that offshore wind energy has more difficulties to be economically used as huge offshore wind power plants in the North of Germany require large extra cost on grid extension within Germany which are considered in the RESlion model.

Figure 24: Capacity comparison for Germany between results of PRIMES and RESlion (RES35-80FDC, 2050)

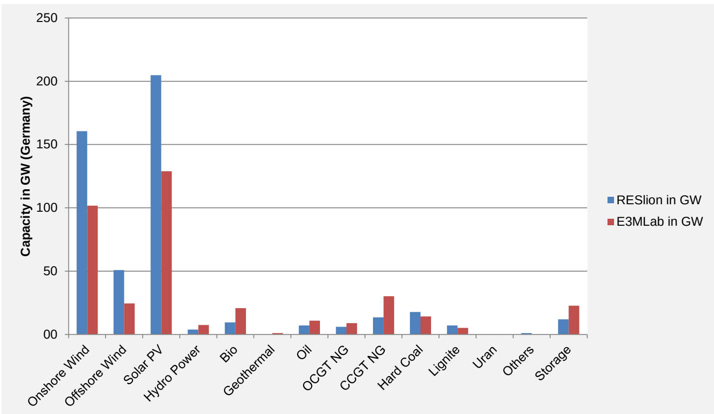
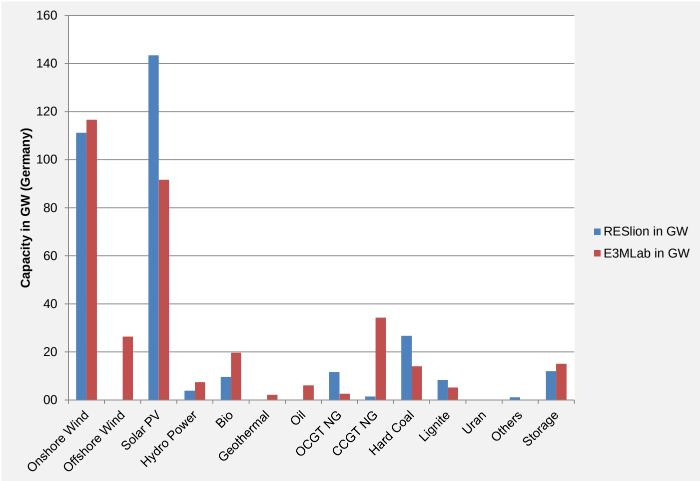


Figure 25: Capacity comparison for Germany between results of PRIMES and RESlion (RES35-65_B, 2050)

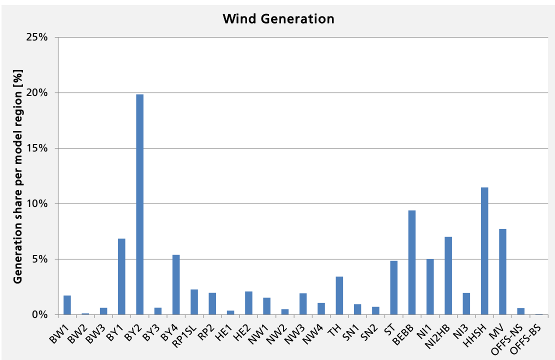


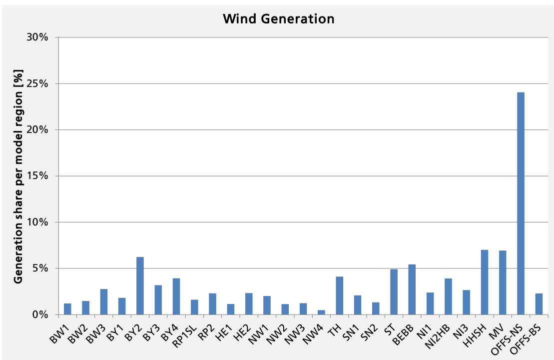
5.2. Regional distribution of RES generation in Germany

Due to the high spatial resolution of the RESlion model, it is possible to analyse the distribution of solar and wind power plants geographically within Germany. The main research question was how both technologies are optimally distributed in Germany if costs for transmission between the North and South as well as increase of international interconnection are considered. In particular, the question could be answered if wind power plants should be only constructed at sites with good resources in the North and PV power plants in the South.

In Figure 26, it is shown that compared to today (or 2020), the wind distribution will be more equal due to the following reasons (scenario RES35-80FDC). Offshore wind power plants are required in high RES scenarios. This leads to large offshore wind generation at the Northern coast of Germany in the North Sea. But onshore wind also in the same area will lead to large transmission extension to the South (as demand is also limited in the North). Therefore, wind power plants in the South should be clearly promoted in the South of Germany after 2020 when large offshore wind projects come online.

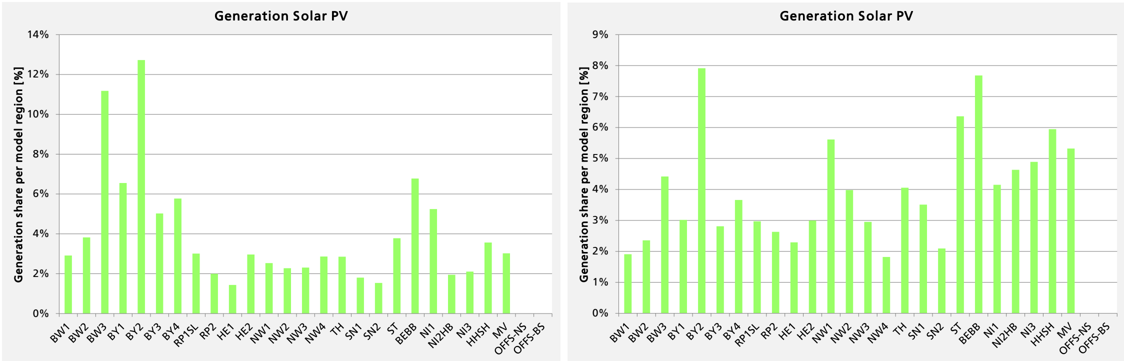
Figure 26: Distribution of Wind energy in Germany in RES35-80FDC scenario (left in 2020, right in 2050)





A similar result is found for PV (Figure 27). Today, PV installations are focused on the South and East of Germany due to high radiation (south, east), availability of land (east) and personal income (south). But an optimal distribution in Germany leads to larger installation in the area of Ruhrgebiet and Rhein-Main due to large demand in these area. However, land access and grid access in both areas has to be available as ground mounted systems can be more expensive in both areas compared to eastern parts of Germany. In the optimal solution for 2050, all areas in Germany have a local generation of 2% to 5% of the overall PV generation in Germany (with some exemptions in Bavaria and around Berlin).

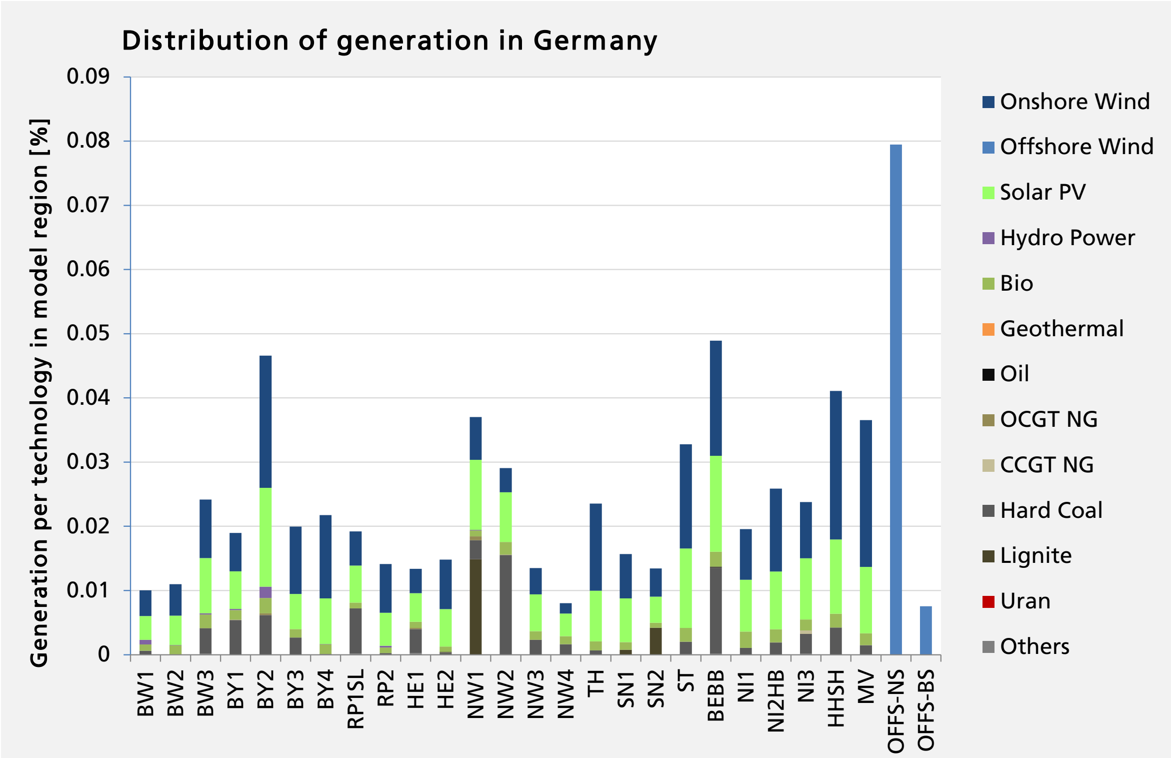
Figure 27: Distribution of PV in Germany in RES35-80FDC scenario (left in 2020, right in 2050)



Overall distribution of generation capacities in Germany in the scenario RES35-80FDC reflects the results of wind and solar (Figure 28). Conventional generation from coal or gas fired power plants are only limited to areas with very high demand as all other regions can be supplied by the RES capacities (which are to some extend also oversized). Offshore wind projects in the North Sea represent a large share of one region compared to the overall generation with over 7% of electricity production located in this region. Due to wind power plants, all Northern regions also represent an area with oversupply and export to the other region, mainly in the West and the South.

In scenarios with lower RES-E shares, the distribution of intermittent RES generation does not have to be that equal as grid extension is lower and conventional power plant balance the unbalanced distribution of RES power plants in Germany.

Figure 28: Distribution of generation per type in German regions in 2050 (RES35-80FDC scenario)



Overall it can be concluded that wind locations in the North are strongly exploited, but to some extend limited and wind generation in the South is a very good alternative if transmission grid extension should be limited (see section 5.4). PV is widely distributed, and it should be planned all over Germany as solar radiation show only differences between 10% and 20% within Germany. Focus to some areas is not cost optimal from a system point of view. Although flexible conventional power generation is required, the analysis shows the use of brown and hard coal until 2050 (also by using high CO2 emission prices). Due to the gas price, gas turbines have only a limited use in the system.

5.3. Regional distribution of RES generation in Greece

For future location and grid planning in the Greek electricity system, the PRIMES results (Figure 29) are analysed in terms of the regional distribution for renewables.

Onshore wind energy shows a high focus to the western and northern part of the country plus installation at the Peloponnese. PV installations are distributed with focus on the North. The main reason for the high share of PV in the North of the country in this scenario is that export to Central Europe is preferred from this region instead of using potentials in the South which require additional transmission lines within Greece.

Also the results for Greece show that a wider distribution of renewables should be reflected in future planning. Different resources in each part of the country provide higher value to the overall system compared to a centralization of renewable power plants.

Figure 29: Generation share per technology in Greece (PRIMES results of RES35-80FDC scenario)

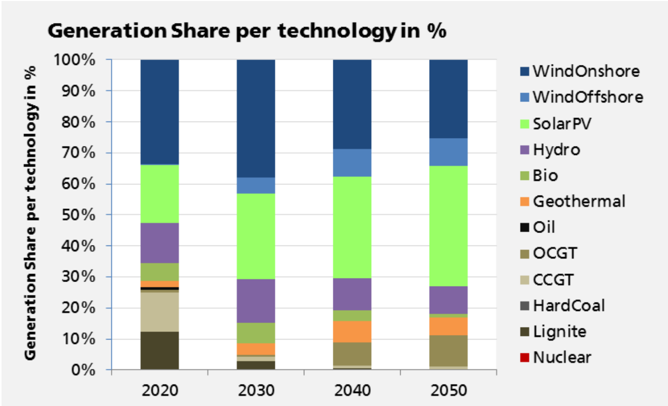
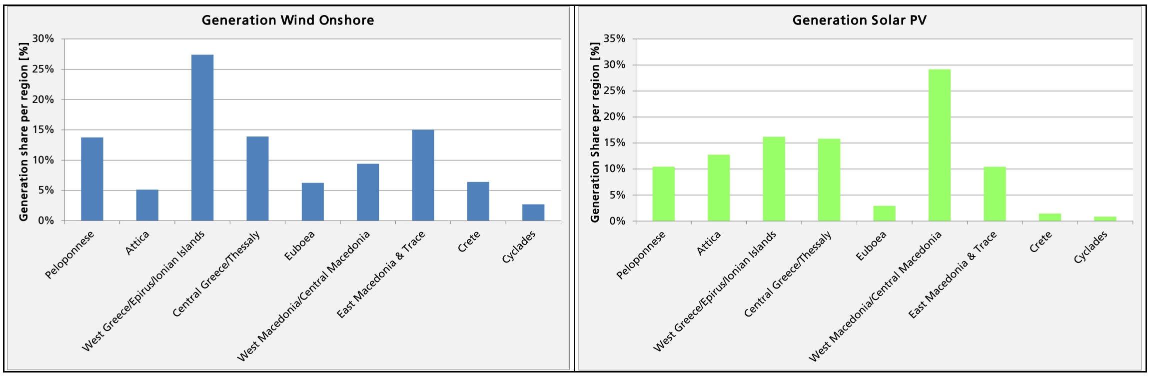


Figure 30: Distribution of renewables in Greece in 2050, RES35-80FDC scenario (left: wind, right: PV)



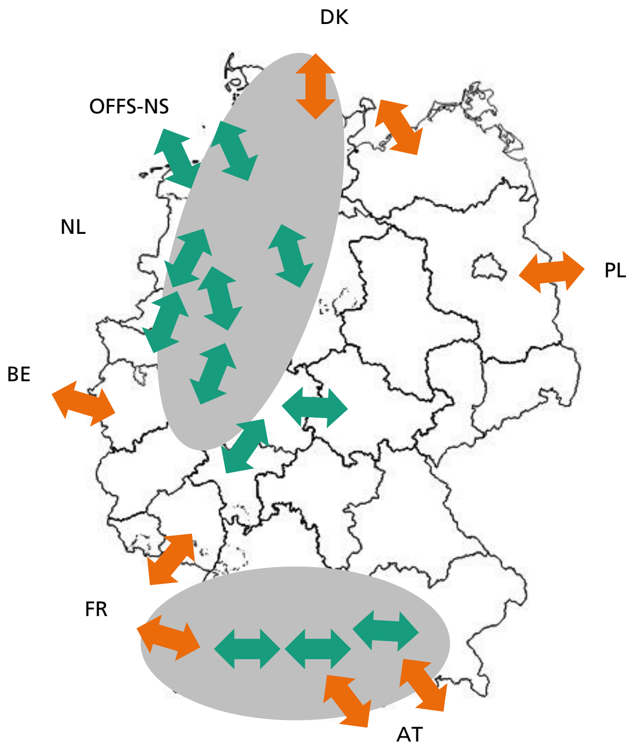
5.4. Sub-national transmission extensions

The sub-national transmission grid has to be extended between all regions in a scenario with high shares of renewables (consequently in all analysed scenarios). However, a focus on grid extension has to be set on to areas in Germany. In Figure 31, all national lines between electricity regions (model nodes) which have to be increased by over 4 GW per connection are marked with green. All international interconnectors which strongly increase their capacity are marked with red.

Due to the volume and distribution of power plants in 2050 in the RES35-80FDC scenario, a strong grid extension between the North-West and the Ruhrgebiet (West) is required. This extension is necessary due to the large expansion of wind power in the North (both onshore and offshore wind energy projects). Additionally, the PV power expansion in the South of Germany requires a strong West-East (also South) link to France and Austria to exchange surplus solar electricity with the neighbouring countries.

Further international transmission lines have to be upgraded in the West to Belgium, the Netherlands and France as well as in the East to Poland.

Figure 31: Grid extension (above average) in Germany until 2050 (RES35-80FDC scenario)



5.5. Electricity exchange between South of Europe (Greece) and Central Europe (Germany)

An increased transmission capacity between Greece and Germany is also tested with the RESlion model. However, some assumptions and limitations are set in the model:

- A direct DC cable between Germany and Greece is analyzed compared to the case of an interconnection Greece-Italy-Austria-Germany in the RES35-65 scenario (sensitivity analysis).
- Balkan countries are not modeled in RESlion due to its geographical scope.
- The size of DC cable is not optimized and set to 10 GW.
- The interconnection Greece-Italy-Austria-Germany (comparison) is fully optimized by RESlion.

The following findings regarding the benefit of an improved interconnection can be found. However, it has to be noticed that also in the basis scenario RES35-65 the required interconnector capacity between the countries Germany (Bavaria), Austria, Italy and Greece are optimally extended to 10 to 20 GW.

An additional 10 GW interconnector which links Germany and Greece directly reduces the overall system costs by 2 bn EUR per year in 2050. This means that the total cost of such a line does not exceeds this value annually. Savings mainly consist of reduce of other transmission lines from Greece to Italy. Additionally, also smaller savings appear in the grid extension between Germany and Austria as well as between Austria and Italy. Annual full load hours are calculated between 2000 and 4000 depending on the generation system in Germany and Greece between 2020 and 2050. The power system in Greece (2050) changes in terms of its wind power and PV installations. With the additional 10 GW interconnector, about 15% higher PV capacity can be installed in Greece and wind power is reduced by 2%. Capacity of Gas power stations is also increased due to the variability of PV. In Germany, the additional interconnector reduces the PV capacity and increases onshore wind capacity (especially in the South).

From this analysis, it can be concluded that the complementary of both electricity system exists and the Greek electricity would prefer to couple its markets not only with Italy (other Balkan countries cannot be analyzed with RESlion). Germany can also benefit from this line as it can use cheap PV electricity from Greece while exporting surplus wind power from Germany to Greece.

5.6. Conclusion

The detailed analysis of the electricity systems in Germany and Greece in scenarios with high shares of intermittent renewable energy source, onshore wind energy and solar PV, provides the following key insights:

- International and national grid extensions are required with a high priority for further increase of RES in the system
- These grid extensions are also economically beneficial compared to other solutions such as conventional back-up or large-scale storage systems
- Regional analysis of Germany and Greece highlights the need for widely distributed RES-E generation to achieve high RES-E targets compared to centralized solutions
- Backup power plants including storages are also required to ensure system stability in all regions
- The national development paths on neighboring countries have a high impact on results (high sensitivity)

6. Conclusion and policy recommendations

The analysis for the RESDEGREE project aims to examine the evolution of the Greek and German power systems in a context of high penetration of renewable energy sources, a context which is not very far from reality considering the trends in EU energy policy. In parallel, the analysis aims to explore how an enhancement of the EU network would allow for better use of the resources of each energy system, allowing to reach high shares of renewables in the energy systems with lower costs, increasing power trade, exploiting synergistically the renewable potential of each country, and sharing flexibility and other system services.

For this purpose the analysis employs two models, the PRIMES model of E3MLab (using two versions of the model including one with enhanced time resolution specifically designed for the RESDEGREE project) and the RESlion model of Fraunhofer ISE. The two models are complementary in terms of

a. EU coverage, with PRIMES simulating simultaneously the operation of all EU countries and neighbouring non-EU countries and RESlion having a more limited scope covering Greece , Germany and their neighbouring countries,
b. time resolution, with PRIMES being limited to maximum 120 representative time segments of a year (in the enhanced version) while RESlion has an hourly resolution and
c. regional resolution, with PRIMES representing every country as a node and RESlion having a higher disaggregation with up to 27 regions in Germany.

Because of these complementarities, the coupling of the two models results in a very detailed modelling suite which has allowed to explore the transition towards RES-based systems looking closely at the details (RESlion) without losing the big picture (PRIMES). Therefore, the results of the modelling exercises although subject to the limitations of the respective models, can be benchmarked to the results of the other model. This way ensures that final conclusions consider both approaches and are not highly sensitive to the limitations of the models.

The analysis shows that the introduction of an interconnection between Greece and Germany allows for a synergistic exploitation of the RES potential between the two countries, as it shows a tendency towards higher solar PV capacities in Greece in parallel to lower wind capacities in Germany. The interconnection allows for a redistribution of the balancing and flexible capacities among the countries that lie along the route of the interconnectors and also neighboring countries, improving their utilization. Power trade develops considerably, with the power lines being used at high rates and propagating benefits to other countries and at the EU-wide level. The interconnection brings also benefits in terms of security of supply, improving reserve margin indicators at national levels.

Employment of the enhanced version of the PRIMES model, with higher time resolution, provides further insights on the impact of the interconnection on flows of electricity; there are considerable complementarities in the impact on flows for Greece and Germany as in many instances the complementarity of availability of RES results in increasing outflows in one country in parallel to increasing inflows to the other. However, impacts are more pronounced for Greece than for Germany, due to the size of the German power market compared to the Greek market and also due to the better interconnection of Germany to other EU countries relative to Greece. The high resolution model also shows that outflows of electricity are increased at times of high variable RES generation while inflows increase to fulfil flexibility requirements. It should be noted that the employment of the enhanced version of the model serves also as a validation of the standard PRIMES model output, as it demonstrates that a system with such high level of RES as projected with PRIMES in the scenarios of the analysis is feasible from an operational perspective.

The described benefits of the interconnection translate also to savings in terms of system costs, with electricity prices reducing not only for the countries that lie along the interconnection route but also for other EU countries who appear to “free ride” on the benefits that the enhancement of the EU system through the Greece-Germany linkage has brought. Moreover, the analysis estimates that such a project would be feasible from a financial perspective as the utilization of the lines is high enough to yield sufficient revenues that ensure a 6% internal rate of return if a price of 6euros per MWh is applied on the flows.

It should be noted that market imperfections are not captured by the model; the analysis of the benefits of the interconnection assumes that the markets that lie along the route of the interconnectors (Balkan region) are functioning properly and that there is wide market-coupling. Moreover, the scenarios assume the perfect functioning of the Internal Energy Market and flow-based allocation of interconnection capacities. In reality, there currently exist significant distortions (e.g. administratively allocation of interconnection capacities) which if they persist would eliminate the benefits of the proposed Germany-Greece interconnection. Moreover, the analysis assumes that the regulatory environment is such that it facilitates the development of the high level of RES observed in the scenarios, removing uncertainties and providing incentives for the uptake of RES technologies.

Therefore, policy making would be required to address the aforementioned issues; removal of barriers for trade, facilitation of the integration of RES and removal of uncertainties in the overall investment environment would allow for the realisation of the benefits described from an enhancement of the network.

The simulations yield an “optimal” level of flows through the interconnections, from the perspective of optimal (least-cost) operation of the national energy systems involved. This level of flows can be established through Power Purchase Agreements (PPAs) at the price recommended by the analysis (6 Euros per MWh). The cost of the PPAs can be socialised allowing third party access and passing it to the consumers. This way the unit cost of the lines will be small and will not counteract the decrease in the average electricity prices induced from the interconnection (as shown in the analysis).

The analysis with the RESlion model looks into the national power systems with more detail and provides concrete policy recommendations for a more efficient integration of RES in the power systems of Greece and Germany. The analysis shows that both the Greek and German energy systems require international and national grid extensions with a high priority for further development of RES to occur. The analysis points out that such grid extensions are economically beneficial compared to other solutions such as conventional back-up or large-scale storage systems. Moreover the analysis indicates the need for widely distributed RES rather than employing centralized solutions in order to achieve high RES-E shares. The role of flexible power plants and storage plants is very significant in order to ensure system stability.

7. Outlook and further research

Within this research project the question concerning the complementarities of renewable energy potential in Europe, especially in Germany and Greece was analysed and assessed. The results showed, that a wide spread harvesting of renewable energy combined with a grid extension will bring assets not only to the countries Germany and Greece, but also to countries in-between, due to a free-riding effect. To strengthen the results further research in the field of intercontinental DC grid to increase the exchange of energy should be performed. Additionally aspects, such as an in-depth analysis of countries, following the DC line extension through Europe will bring innovative and new assessments. One major further aspect, which should be looked at subsequent to the RESDEGREE project is a thorough analysis of the flexibility options in Germany, Greece and Europe and its interdependency with a highly developed grid within the countries as well as between the countries. Building on top of the Project RESDEGREE and the coupled model suite with PRIMES and RESlion, the above described questions for further research can be addressed. Hereby especially the complementarity of the models can be used as an asset.

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