FlexPlan

Advanced methodology and tools taking advantage of storage and FLEXibility in transmission and distribution grid PLANning

Pan-European Simulation Results

D4.2

Distribution Level	PU
Responsible Partner	TU Dortmund
Checked by WP leader	Jawana Gabrielski (TU Dortmund) – WP4 Leader Date: 01.03.2021
Verified by the appointed Reviewers	Izabella Faifer (RSE) – Date: 05.03.2021 Andrei Morch (Sintef) – Date: 10.03.2021
Approved by Project Coordinator	Gianluigi Migliavacca (RSE) Date: 26.03.2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863819

Issue Record

Planned delivery date	31/03/2021
Actual date of delivery	26/03/2021
Status and version	FINAL

Version	Date	Author(s)	Notes
V0.1	18.12.2020	Jawana Gabrielski	Creation of Table of Contents
V0.2	25.02.2021	Nuno Amaro	Contribution on Scenario Data from D.4.1
V0.3	01.03.2021	Jawana Gabrielski	Finalization of First Draft for Internal Review
V0.4	10.03.2021	Izabella Faifer, Andrei Morch, Gianluigi Migliavacca	Internal revision completed
V0.5	25.03.2021	Jawana Gabrielski	Inclusion of feedback from internal reviewers
V1		Jawana Gabrielski, Gianluigi Migliavacca	Final revision

About FlexPlan

The FlexPlan project aims at establishing a new grid planning methodology considering the opportunity to introduce new storage and flexibility resources in electricity transmission and distribution grids as an alternative to building new grid elements. This is in line with the goals and principles of the new EC package *Clean Energy for all Europeans,* which emphasizes the potential usage of flexibility sources in the phases of grid planning and operation as alternative to grid expansion. In sight of this, FlexPlan creates a new innovative grid planning tool whose ambition is to go beyond the state of the art of planning methodologies, by including the following innovative features: integrated T&D planning, full inclusion of environmental analysis, probabilistic contingency methodologies replacing the N-1 criterion as well as optimal planning decision over several decades. However, FlexPlan is not limited to building a new tool but it also uses it to analyse six regional cases covering nearly the whole European continent, aimed at demonstrating the application of the tool on real scenarios as well as at casting a view on grid planning in Europe till 2050. In this way, the FlexPlan project tries to answer the question of which role flexibility could play and how its usage can contribute to reduce planning investments yet maintaining (at least) the current system security levels. The project ends up formulating guidelines for regulators and for the planning offices of TSOs and DSOs. The consortium includes three European TSOs, one of the most important European DSO group, several R&D companies and universities from 8 European Countries (among which the Italian RSE acting as project coordinator) and N-SIDE, the developer of the European market coupling platform EUPHEMIA.

Partners

Table of Contents

About FlexPlan 3
Table of Contents 4
List of Abbreviations and Acronyms 5
Executive Summary 6
1 Introduction 7
1.1 Placement of this Deliverable within the FlexPlan Project 8
2 Input Data 9
2.1 Scenario data 9
2.2 Transmission Grid Node Location and Power Plant Data 10
2.2.1 Power Plant costs and operational information 10
2.3 Structural Data 10
2.3.1 Land Use and Land Cover Data 10
2.3.2 Population density data 11
2.4 Weather Data 11
3 Methodology 12
3.1 Energy Meteorology 13
3.1.1. Transforming numerical weather data in electrical power outputs 13
3.2 Regionalization 13
3.2.1 Spatial Distribution 14
3.2.2 Time Series Generation 17
3.3 Market Simulation 22
4 Results 26
.... 32
5 Conclusions 32
6 Bibliography 34
7 Annex 36

List of Abbreviations and Acronyms

Abbreviation/Acronym	Meaning
CLC	CORINE Land Cover
CORINE	Coordination of Information on the Environment
DWD	German Weather Service (German: Deutscher Wetterdienst)
ENTSO-E	European Network for transmission System Operators for Electricity
EU	European
MAF	Mid term Adequacy Forecast
MILES	Model of International Energy Systems
NTC	Net Transfer Capacity
OPF	Optimal Power Flow
PSP	Pumped Storage Power plant
PV	Photovoltaic
RES	Renewable Energy Sources
RoR	Run of River
TPP	Thermal Power Plant
TYNDP	Ten Year Development Plan
WTG	Wind Turbine Generator

Executive Summary

This deliverable provides information on the methodology and the output of the pan-European market simulations carried out within the FlexPlan project. The results will serve as input data for the six detailed regional cases, which will be executed in the scope of the FlexPlan project in order to validate and apply the developed FlexPlan tool. This will allow to cast a view on the role flexibility will have until the year 2050 and prepare the ground for the development of regulatory guidelines. For the pan-European simulation, previously a complex scenario data collection and processing task was executed, which identified the three scenarios described in TYNDP 2020 [1] as the main source for scenario data and extended the data, which is solely available for the years 2030 and 2040, to the year 2050. As this data is provided on a national level, it needs to be disaggregated to a regional level, in order to feed the regional cases with nodal information that is coherent with the overall scenario. Furthermore, boundary conditions are needed, providing a common ground for the interrelated regional cases. For this, a pan-European simulation is carried out, applying the electricity market and transmission grid simulation framework *MILES* [2].

The results of the pan-European simulation include mainly the following information:

- Regional Time Series: To generate regional time series for the hourly power injection of renewable energy sources and loads, a Regionalization methodology is applied, which is one module of *MILES*. The methodology uses national scenario data for different scenarios and target years as input data and generates time series following a two-step approach. First, the national data is distributed to a regional level; as the results are to be used for the regional cases, the regions are defined as the node locations of the transmission grid. The installed capacities are assigned to these nodes using structural data, i.e. population density. In a second step, based on the nodal installed capacities, time series are generated by means of regional weather data for renewable energy sources as well as on historical load profiles for the demands. Finally, the obtained time series are scaled considering the required energy provided in the scenario data.

- Cross Border Exchanges: Taking into account the time series for renewable energy sources and loads, which were calculated before, the market simulation module of *MILES* runs an integrated unit commitment and dispatch model and determines power plant and storage schedules, as well as cross border power exchanges between European countries. The power plant deployment optimization takes into account different constraints i.e., the reserve power to be maintained, available transmission capacities between the countries and the technical, partly time-coupling restrictions of the generation units and storage facilities. The resulting power exchanges allow to adopt a consistent set of border conditions for the power flow exchanged between the areas described by the six regional cases.

This document provides a full description of the used input data, the methodology adopted for pan-European simulations as well as the results, establishing a basis for the regional case studies, which will use these data for their simulation.

1 Introduction

FlexPlan is developing an innovative grid planning tool, which will be run with different scenarios by six regional cases covering almost the whole European (EU) power system in order to investigate the role of flexibility until the year 2050. **Figure 1-1** indicates the perimeter of the six regional cases. In order to run the regional cases individually, a consistent set of boundary conditions is needed, regarding the power flow exchanges between the different regional cases. For this, pan-European simulations are carried out, which determine the hourly schedules of power plants as well as the cross-border power exchanges. As the injection of Renewable Energy Sources (RES) depends on the available primary energy, which varies locally, in a first step a regionalization methodology is applied, which spatially distributes national installed capacities to a regional level and generates time series based on regional weather conditions for RES and historical load profiles for the demand. The obtained time series are used as input data for market simulations, which determine schedules for thermal power plants (TPP) and storages as well as cross-border exchanges. The resulting time series as well as the cross-border conditions serve as input data for the regional cases.

The employed input data, the detailed methodology as well as the obtained results are documented in this deliverable.

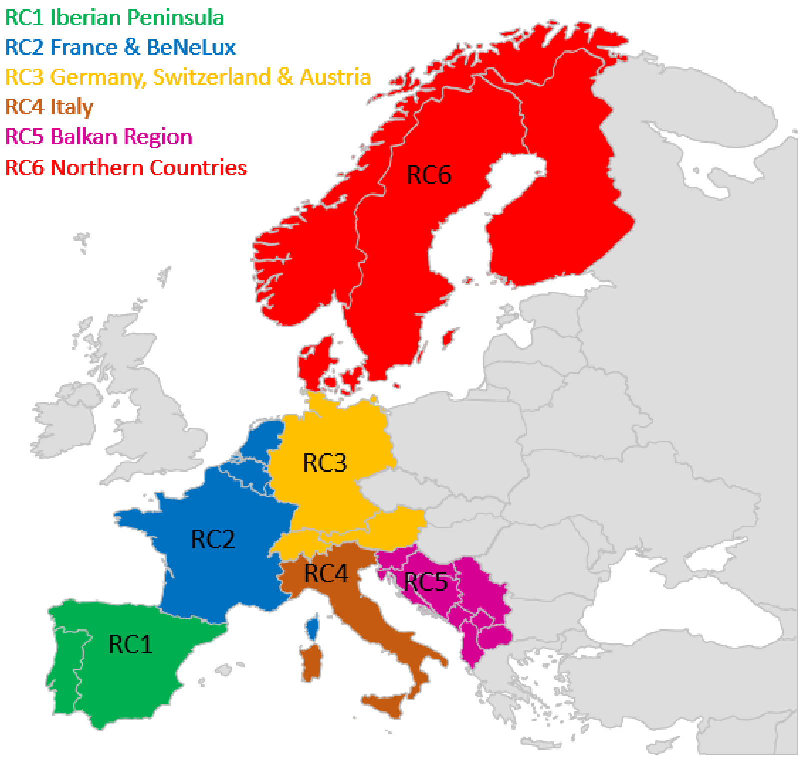


Figure 1-1: Regional cases

1.1 Placement of this Deliverable within the FlexPlan Project

FlexPlan establishes a new grid planning methodology, which includes many different tasks. The conceptual block diagram depicted in **Figure 1-2** visualizes the FlexPlan research perimeter and the applied approach. The scope of this deliverable as well as the interdependencies to other tasks are marked in blue.

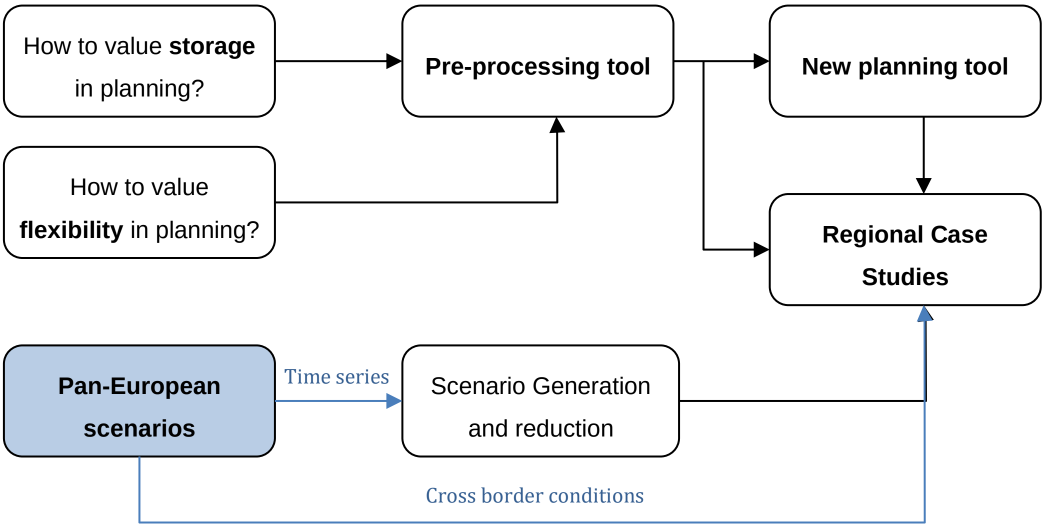


Figure 1-2: FlexPlan project conceptual block diagram

The project core consists of the conceptual design and realization of the new planning tool. Furthermore, technologies for flexibility provision are analyzed in depth and feed a pre-processor tool providing indications for the sizing and location of storage candidates and loads to be exercised in a flexible way, as well as candidate line reinforcements and grid expansion options. All this is provided as an input to the optimization model implemented by the advanced planning tool. More information about the pre-processing tool is to be found in deliverable D2.3 [3].

In parallel to the development of the new planning tool, pan-EU scenarios are created for the years 2030, 2040 and 2050 based on well-established EU and national "visions" as well as on the ENTSO-E's (European Network for transmission System Operators for Electricity) Ten-Year Network Development Plan (TYNDP) [1], EU targets for the upcoming decades, national regulations, and other relevant aspects such as climate targets. The developed scenarios consider different restrictions concerning primary energy resources, e.g., coal, gas or nuclear fuel, due to sociopolitical and economic aspects. The methodology adopted for generating FlexPlan scenarios is described in detail in deliverable D4.1 [4].

The development of scenarios at a pan-EU scale would require extensive simplifications due to computational restrictions, which are not suitable for detailed network planning studies. Thus, six regional cases are developed in order to carry out detailed planning studies for the main EU macro-zones considering transmission and distribution grid infrastructures in detail, so as to obtain the optimal grid expansion plan for each considered regional case. However, in order to apply coherent border conditions for all regional cases, pan-EU simulations are executed first. These pan-EU simulations are the object of the present deliverable. In order to build up the input set for the pan-EU simulations, the scenario data is first spatially distributed to a regional level and time series for RES and load are generated. For this, a regionalization methodology is used. Since, the results are to be used for the regional case's grid calculations, the node locations of the transmission grid are considered as the regions. Based on the obtained time series, market simulations are run in order to determine an integrated unit commitment and dispatch of the EU system and calculate optimal schedules for TPP and storage. With the same simulations, cross-border power exchanges between EU countries are determined and used as border conditions for the regional cases. The regional time series of RES and load are furthermore used to calculate a non-expanded Optimal Power Flow (OPF) during the regional case execution.

Hourly power injection patterns of RES generators are first calculated using weather data for one specific year without consideration of stochastic inputs. Subsequently, in order to consider uncertainty concerning variable RES a specific scenario generation approach is applied, by taking into account different weather years. This approach is presented in deliverable D1.1 [5].

The regional scenario data serves as an input for the preprocessor tool as well as for the planning tool. The planning tool receives, besides the regional scenario data, the pre-processor results in terms of potential locations of flexible devices (storage and flexible load) and potential transmission expansion candidates. All of them are considered as binary optimization variables. The FlexPlan planning tool carries out an optimal choice among such "candidates". In this way, the optimal grid expansion plan for each considered region is identified.

This deliverable *Pan-European Simulation Results* includes:

- description of the used input data (section 2),
- presentation of the methodology for the regionalization, containing spatial distribution as well as time series generation, and for the market simulation (section 3)
- illustration of the pan-EU results for one scenario (section 4).

2 Input Data

Before explaining the methodology for the pan-EU simulation, an overview of the used input data will be given in the following section. It includes data, which was elaborated within the project, e.g., the defined scenario data, as well as data from other sources, i.e. structural data, which is needed for the regional distribution.

2.1 Scenario data

In the scope of FlexPlan, three energy scenarios based on those defined in the TYNDP 2020 by ENTSO-E [1] are established for each of the three target years: 2030, 2040 and 2050. The activities dedicated to the data collection and validation process to create these scenarios as well as the scenario data are documented in the project deliverable D4.1 [4].

The three scenarios include data which can be grouped in seven categories:

- Installed generation capacities by technology;
- Annual mean capacity factors for RES;
- Annual electricity consumption and peak load;
- Hourly time series data for consumption;

- Net transfer capacities (NTCs);
- Commodity prices for different types of fuel for nuclear and fossil power stations;
- Total operational reserve power.

This data is provided at national level.

In order to collect the necessary scenario data at a pan-EU level, by taking into consideration the wide range of the regional cases and the need to perform pan-EU simulations, the TYNDP 2020 from ENTSO-E [1] was considered as a common data source, ensuring that most of the required data is available. Using this data source, it was possible to create 2030 and 2040 scenarios.

As TYNDP 2020 does not contain data at national level for 2050, a two-step methodology was implemented to create the corresponding 2050 FlexPlan scenarios. The first step corresponds to a linear interpolation of available 2030 and 2040 data while the second step corresponds to an adaptation of obtained values using "A Clean Planet for All" long term strategy from the EU Commission [6] as comparative source. As TYNDP 2020 scenarios are built already using this strategy as a background data source, the validation process was straightforward ensuring the coherence of the three scenarios and three target years.

2.2 Transmission Grid Node Location and Power Plant Data

As the described scenarios are to be simulated using realistic grid models, representative for transmission systems of the different regional cases and additional data sets are required. These additional data needs include the identification of transmission grid nodes location and power plant related data. These datasets enable the matching between scenarios and grid models, allowing to distribute generation and load values to a nodal level. The location of grid nodes was provided by each one representative of the regional cases, for the grid of each respective regional case, while for the creation of the power plants database, an open source was used – PowerPlantMatching [7]– also complemented with data coming from each one of the regional cases. The methodology is described in detail in D4.1 [4].

2.2.1 Power Plant costs and operational information

The Mid-term Adequacy Forecast (MAF) from ENTSO-E [8] is the main source for information about power plant characteristics. The MAF is an assessment of power system resources adequacy on a pan-EU level. The report contains an extensive dataset for average operational power plant data, i.e., ramping rates and minimal stable generation as well as cost data e.g., start-up costs.

2.3 Structural Data

The spatial distribution of RES and loads requires among others structural data for the considered regions. Two parameters involved are data for land use and population density data, which will be described in the following.

2.3.1 Land Use and Land Cover Data

CORINE (*Coordination of Information on the Environment*) Land Cover (CLC) [9] data is used as the source for information on land use and land cover. CLC is an EU project that developed a uniform classification for the most important kinds of land covers all over Europe. For this, digital satellite images are collected and analysed with regard to the land use and maps are built. The land cover is distinguished between 44 different classes. The data is provided in a 100 m^2 grid. **Figure 2-1** shows this data; the legend for the different land classes is additionally provided in the Annex of the present report.

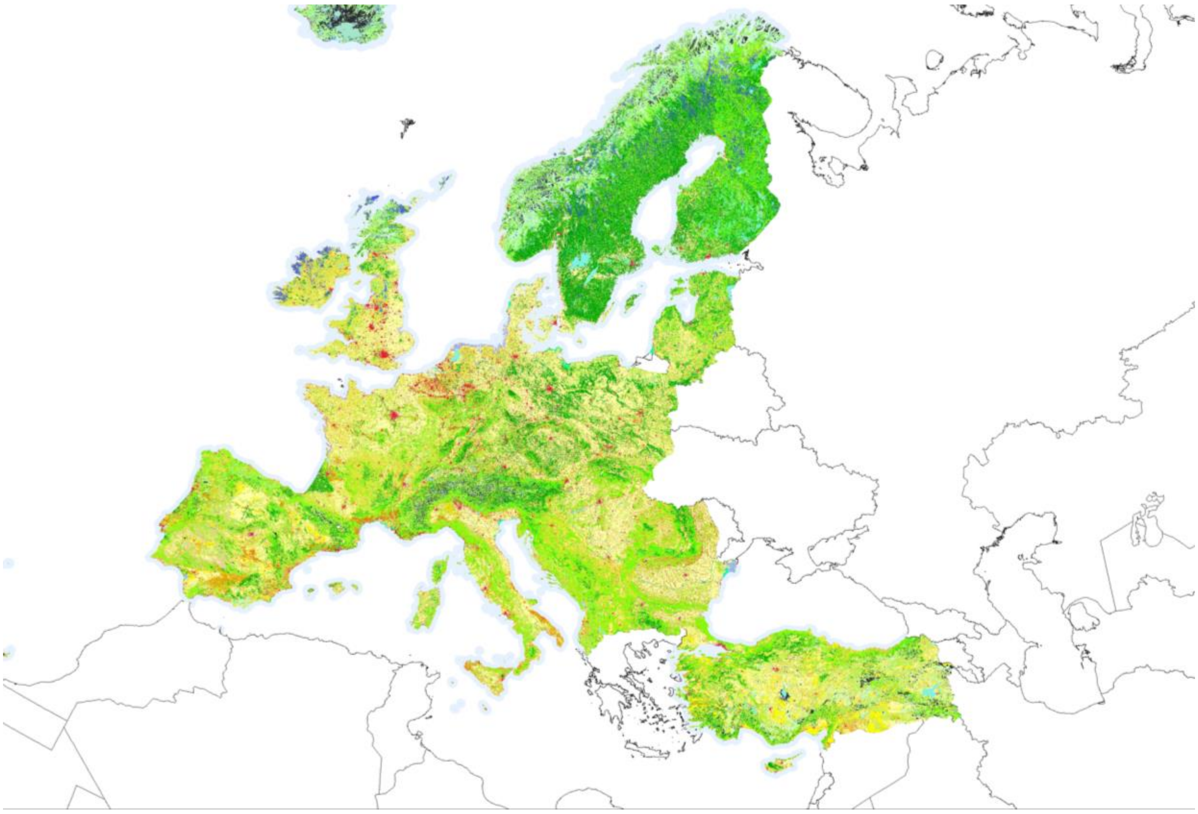


Figure 2-1: Corine Land Cover Data, source: [9]

2.3.2 Population density data

Population density data is used from the Geostat [10] data source, which is elaborated by Eurostat. The data set provides information on a 1 km^2 grid for most of the EU countries.

2.4 Weather Data

To determine the time series, meteorological data from the COSMO-EU model [11] of the German Weather Service (DWD) are used. The data are available for a grid with a mesh size of 7 km throughout Europe. The time series of wind speed and solar radiation, the temperature at 2 m and 116 m altitude as well as the albedo of the ground are taken. For the simulations described in this deliverable the weather year 2012 is considered.

3 Methodology

The methodology, which is applied for the pan-EU simulation is based on the market and network simulation environment MILES (Model of International Energy Systems) [2] [12], a tool chain, which was developed at TU Dortmund over several years. *MILES* enables techno-economic analyses of the pan-EU energy system and covers the entire process chain of network development planning. It consists of several coherent modules. Within the FlexPlan project, in particular the regionalization module and the market simulation module are used. *MILES* does not only simulate the countries, which are considered within the FlexPlan project, but also the surrounding EU countries (see Figure 3-1), which enables to take into account cross border effects on all regional cases.

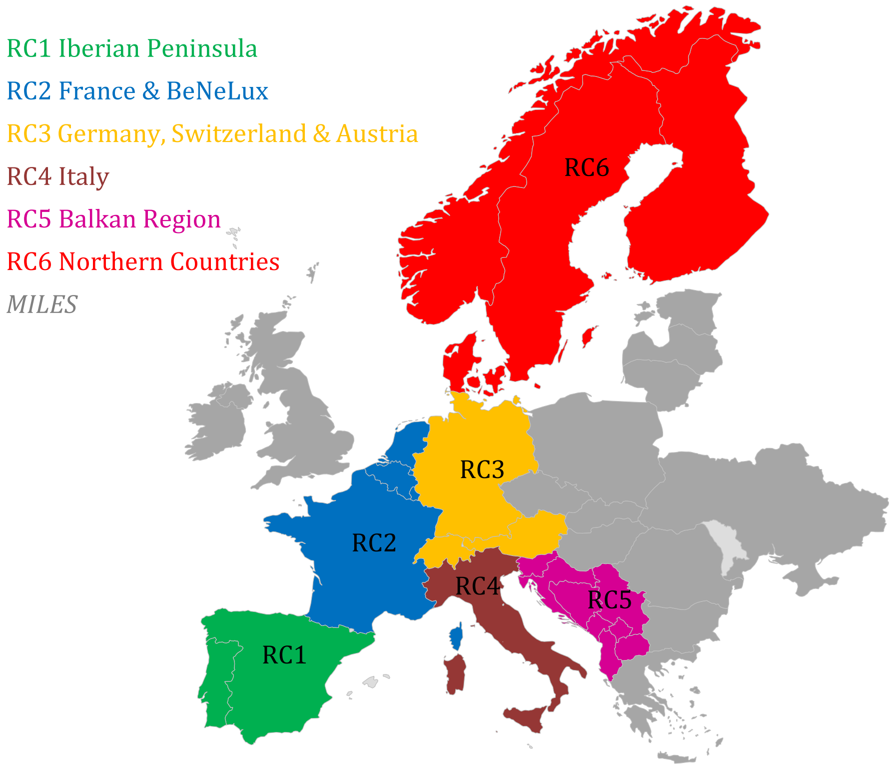


Figure 3-1: Countries considered in *MILES*

In the regionalization module, firstly, the forecasted capacities of RES and the load are regionally distributed for the considered areas. Secondly, hourly time series are generated based on historical consumption and weather data for electrical loads and different types of renewables. [12] Subsequently, during the market simulation the minimum cost use of conventional power plants and storage facilities in EU is determined for each reference planning year (2030, 2040, 2050) and with an hourly resolution. In addition to the schedules of conventional power plants and storage facilities, the simulation also calculates the power flow exchanges between all countries under consideration. [2]

MILES is dedicated to system studies with a strong focus on the German system. Within FlexPlan, *MILES* is applied to all pan-EU countries and thus in particular the regionalization methodology is adapted to the different countries' individual geographic circumstances.

The regionalization methodology deals with weather dependent RES, using the basis of energy meteorology. Hence, the next subsection provides a short overview on energy meteorology.

3.1 Energy Meteorology

For a long time, due to predominantly fossil-based energy systems, which used storable and transportable energy sources (coal, lignite, oil, natural gas and nuclear), meteorological topics were only of minor importance for energy system analysis. This situation already changed fundamentally at the turn of the millennium with increasing deployment of RES. This led to the foundation of the still young field of energy meteorology. In particular, the renewable primary energy sources wind and solar are planned as fundamental components of energy generation in the future energy system. However, these cannot be stored and are volatile in their supply. Due to this increasing weather-dependent energy production, comprehensive information about the spatial and temporal availability of these energy sources is needed to simulate the energy system [13].

In addition, a detailed understanding of the influence of meteorological parameters is necessary in the planning of the future energy system. Power generation of intermittent RES is mainly determined by their location and the corresponding local climatic conditions. To capture and describe these interactions between meteorological and energy processes, existing meteorological models are used. These numerical simulation models map the physical effects of the atmosphere based on the basic equations for momentum, mass and energy conservation as well as further balance equations for cloud water, rainwater and precipitation particles. One result is a three-dimensional wind field, which considers the influence of orography in layers close to the ground. For example, the influence of forests or settlements is mapped as well as the increase of wind speed over crests and mountain ridges. Thus, by the application of numerical weather models inaccurate extrapolations of data from near-ground measuring stations to determine the wind speed at different heights, e.g., hub height of a WTG (Wind Turbine Generator), can be avoided, as this process typically goes along with increasing uncertainty depending on the height. [14] [15] [16]

3.1.1. Transforming numerical weather data in electrical power outputs

For Power system studies, such as transmission expansion planning, the feed-in of all generators is required as an input. Thus, the feed-in of non-dispatchable RES, like wind and solar, has to be modeled. For this, the meteorological information of numerical weather models has to be converted into electrical power output. In contrast to statistical models, physical models make use of turbine power curve functions to transform the wind speed to electrical power generation. Subsection 3.2.2 explains in detail how this is realized in *MILES*.

3.2 Regionalization

Network development plans as well as the FlexPlan scenario data provide information on loads, planned installed capacities of power plants as well as generated energy for RES for future years. This information is given at a national level, but it does not include information on where in the country new RES will be located and when the power will be generated. However, this information is necessary to calculate the power flow and determine congestions in future grids. Hence, a methodology is applied to spatially distribute RES as well as loads and generate time series considering regional weather data.

For this, a two-step approach is used. First, the forecasted capacities of RES and the load are regionally located for the pan-EU countries. The regional installed capacities are determined by distributing the national installed capacities, taking into account structural data as well as information on existing and firmly planned power plants. As the regional installed capacities are needed for the subsequent power flow calculation, the results are assigned to the locations of the transmission nodes. Time series are then generated on the basis of historical consumption and weather data for electrical loads as well as for different types of renewables. The conceptual block diagram depicted in **Figure 3-2** outlines the procedure as well as input and output data. The data marked in blue, was elaborated within the FlexPlan project.

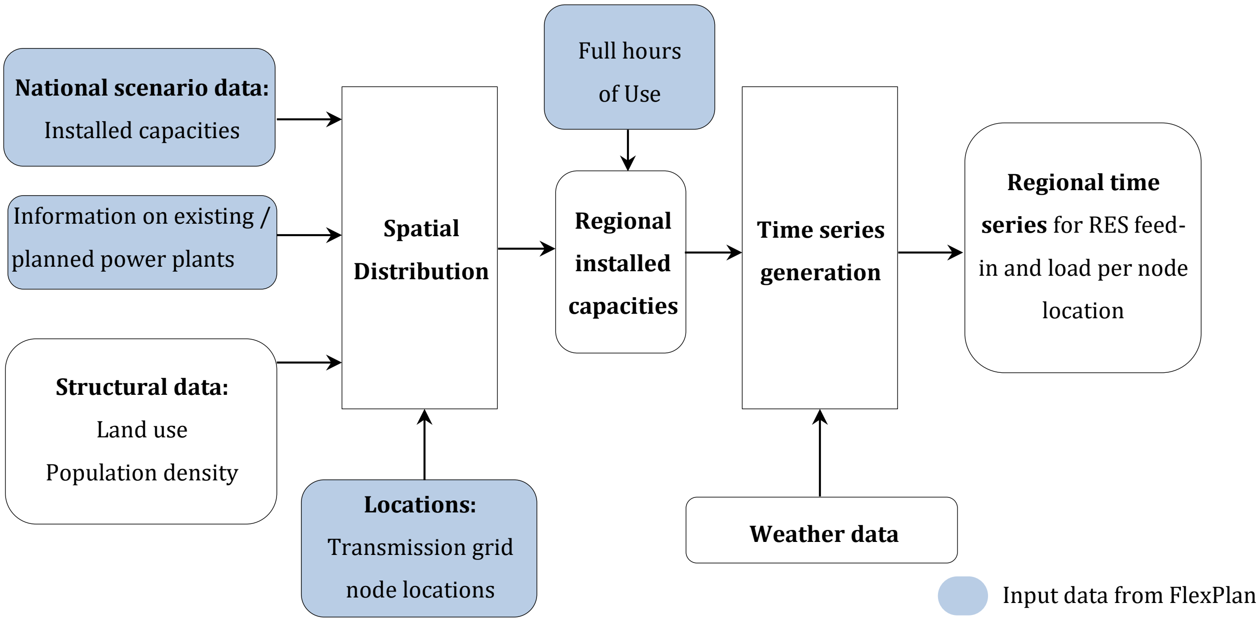


Figure 3-2: Conceptual block diagram of the regionalization

3.2.1 Spatial Distribution

The regional distribution of RES is based on information on existing power plants and loads as well as regionalization factors for future RES. Information on the location of existing and planned RES is based on information from power plant matching, which was extended by the regional partners, as described in subsection 2.1. Since, this information is gathered from different sources, it is a very heterogeneous database. Whereas, for some countries, almost the entire installed capacity from the scenario data is covered by the database, in other cases it is only a fraction. If the complete installed capacity is almost known in terms of existing and planned power plants, it is very likely that prospective plants will be close to the existing infrastructure. Hence, in some cases upscaling of the existing installed capacity is the easiest and most accurate way to determine the future spatial distribution. However, if the share of existing power plants is quite low, another methodology is used.

As opposed to the existing and explicitly planned power plants, the location of future power plants is unknown and is thus determined based on structural data, like land cover data and population density. The data and their sources are described in subsection 2.3. The structural data is applied to form statistical parameters, which represent proportionalities between land use and installed capacities of RES. For this, regionalization factors are used. Regionalization factors ($F_{Regionalization}$) describe the percentage of the total installed capacity, which is installed in the considered region (F^{n}_{Region}). There are two kinds of regionalization factors: one-dimensional ($n = 1$) and multi-dimensional ($n > 1$) factors. One dimensional factors use one set of input data. To calculate a multi-dimensional regionalization factor a main parameter and a weighting factor are needed. [12]

$$F_{Regionalization} = \frac{\prod F^{n}_{Region}}{\sum_{Region} \prod F^{n}_{Region}}$$

Using wind energy as an example, a one-dimensional factor would be the relation of agricultural area in the region, compared to the whole agricultural area in the country. For a two-dimensional factor the first factor (agricultural area) is weighted, by a second factor, in this case, reciprocal to the population density in the considered area. As a result, more plants are installed in areas with lower population density.

Due to meteorological variations between the different countries and differences in the data basis, it is not possible to use the same approach for all the countries. Hence, the countries are clustered if necessary and different methodologies are applied. As the geographical requirements of different RES depends on several factors, the regionalization factors are determined for each technology separately.

Photovoltaic Power Plants

For Photovoltaic (PV) it has to be distinguished between countries with high solar irradiation and countries with less solar irradiation. In countries with poor solar irradiation most of the PV power plants are private and mostly placed close to the consumer, i.e., on rooftops, as opposed to countries with high solar irradiation, where PV systems are mainly ground mounted. The division between the countries is done, according to an average irradiance comparison. For countries with low solar irradiation, it is assumed that PV plants are mainly located in urban areas. In southern countries with higher solar irradiation it is assumed, that PV systems are mainly installed on non-irrigated arable land. [17] **Figure 3-3** shows the classification as well as the average irradiation.

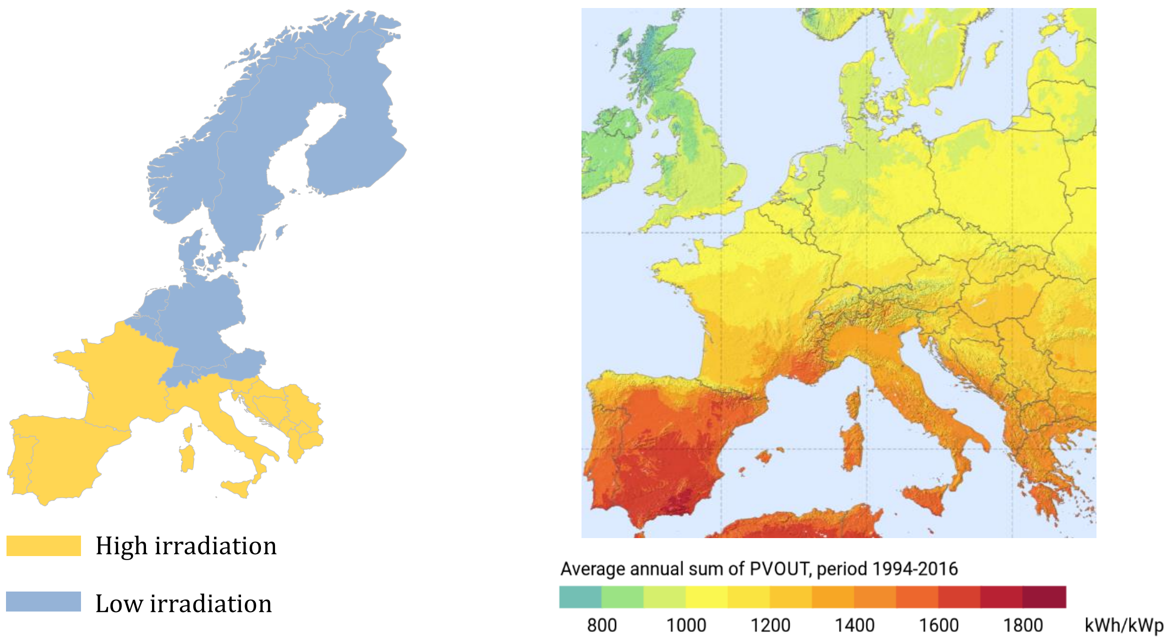


Figure 3-3: Comparison of Solar Irradiance in Europe, right source: [27]

Wind Turbine Generators

There is a limited number of locations with excellent conditions for WTGs. Since, WTGs were built at these locations first some time ago and they have a limited life time, it is very likely that new larger WTGs will replace them and will be built at the same locations. In order to consider this within the methodology, the installed capacity of existing plants is scaled up (P_{up}). However, the upscaling has to be done carefully considering the proportion of the existing power plants compared to the installed capacity defined by the scenario ($share_{ex}$). Hence, the upscaling is done proportional to the share of existing plants, as shown in the following equation. If the share of existing power plants exceeds a certain threshold, the existing plants are scaled to the target installed capacity.

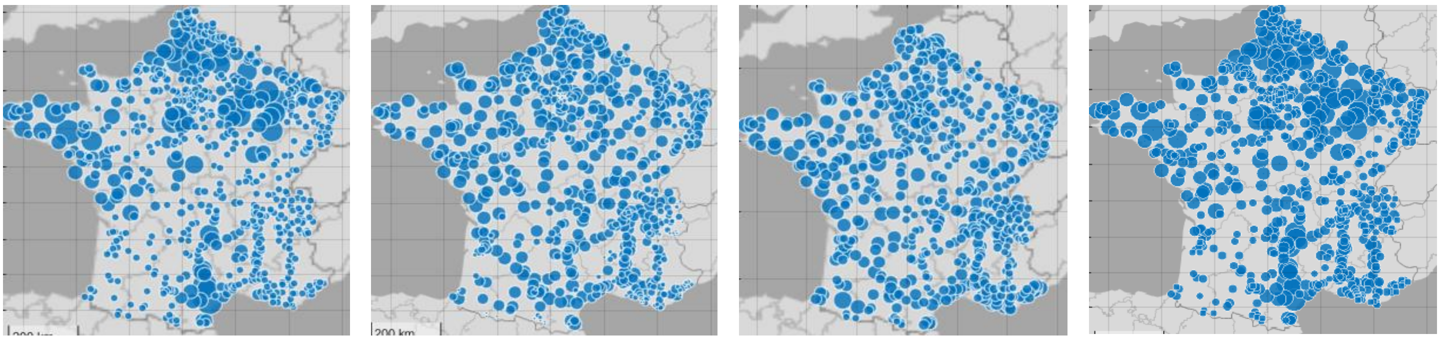
$$share_{ex} = \frac{P_{existing}}{P_{scenario}}$$

$$P_{up} = \begin{cases} P_{existing} * 1/share_{existing} & share_{ex} > share_{threshold} \\ P_{existing} \cdot 2 \cdot share_{existing} + Region \cdot (1 - 2 \cdot share_{ex}) & share_{ex} \leq share_{threshold} \end{cases}$$

Since, the installed capacity increases during the time horizon, the definition of the threshold takes into account the scenario year.

$$share_{threshold} = \begin{cases} 0{,}4 & scenarioyear = 2030 \\ 0{,}3 & scenarioyear = 2040 \\ 0{,}2 & yscenarioear = 2050 \end{cases}$$

Assuming, that WTGs are mainly installed in sparsely populated agricultural areas, the regionalization factor for wind uses agricultural land data, weighted reciprocal to the population density. **Figure 3-4** demonstrates the exemplary methodology for the spatial distribution in France. Part a) shows the distribution of the existing plants, which are scaled up. The second part, b) visualizes the number of agricultural areas in each region and the population density is depicted in part c). Part d) shows the resulting wind distribution, considering the aforementioned parameters.



a) Existing plants b) Agricultural areas c) Population density d) WTG distribution

Figure 3-4: Spatial Distribution of WTGs in France

Hydro Power Plants

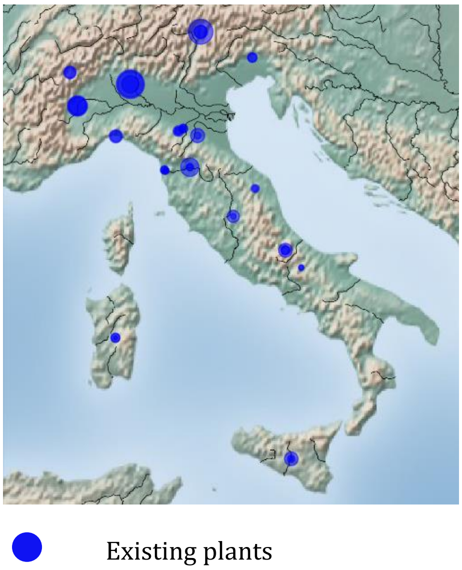


Figure 3-5: Installed hydro capacity in Italy

Hydro power plants can be distinguished between Run of River (RoR), reservoir and Pumped Storage Power (PSP) plants. As PSP plants do not depend on meteorological circumstances, they are not considered during the regionalization, but in the market simulation. RoR and reservoir power plants are always located at locations with specific circumstances. Since, there are many factors influencing whether a location is suitable for a new plant, a simplification is used, assuming that new plants will be build close to existing ones. Hence, existing power plants are scaled up to fit the installed capacity of the scenario data separately for RoR and reservoir power plants. In order to limit the size of a plant it is assumed that the extrapolated plants are not only connected to the closest node but also to the surrounding nodes, which are up to a distance of 30 km from the plant. **Figure 3-5** shows exemplary results for Italy.

Load

The spatial distribution of the load is proportional to the population density. Hence, a one dimensional regionalization factor is used, taking into account the population density data, described in section 2.3.2.

3.2.2 Time Series Generation

In the following, the time series determination of PV systems, wind and hydro power plant deployment optimization are presented in more detail. In addition to a description of the individual models, an explanation of the parameterization is also given. Based on the installed renewable energy determined within the scope of spatial distribution, the feed-in time series of the respective energy sources are determined. For this, meteorological data, which is described in section 2.4 is used. The procedure for determining the feed-in time series of WTGs, PV and hydro plants is described below.

Standardized power supply of the wind turbine generators

For each grid node the time series of the standardized feed-in power of a WTG is calculated using the time series of wind speed. The power curve of a WTG is determined by varying the wind speed at the height of the hub v_{hub} and under addition of the rotor surface A_{R} of the characteristic value of the plant (coefficient of power) c_P and the local air density ρ_L is calculated according to [14] as follows:

$$P(v_{\mathrm{Nabe}}(t)) = 0{,}5 \cdot \rho_{\mathrm{L}} \cdot A_{\mathrm{R}} \cdot c_P(v_{\mathrm{hub}}(t)) \cdot v_{\mathrm{hub}}^3(t)$$

The characteristic curve used, describes the performance of an average WTG on the basis of its coefficient of performance according to the current state of the art (see [18] for derivation). The characteristic curve is shown **Figure 3-6** compared to 47 characteristic curves of the WTGs from [19], which were used for its derivation.

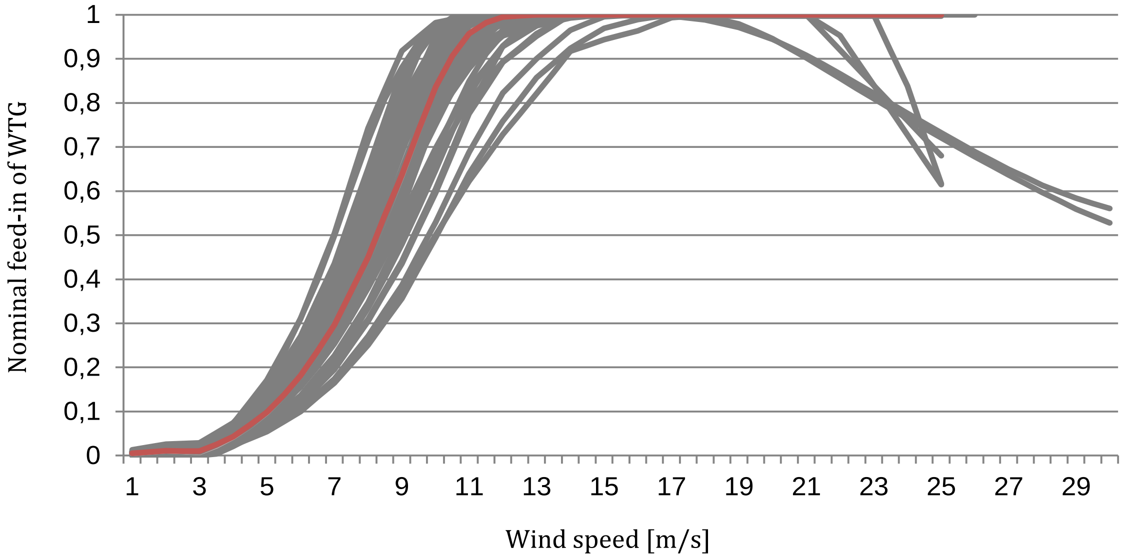


Figure 3-6: Comparison of characteristic curves with the characteristic curves of other WTGs [19]

The simulated plants do not have storm control, but a storm shutdown. In concrete terms, this means that the turbines switch off at wind speeds above 25 m/s and do not provide any electrical power. On the basis of the standardized power curve, the wind speed can be transferred to the standardized feed-in of a WTG at any node and at any time.

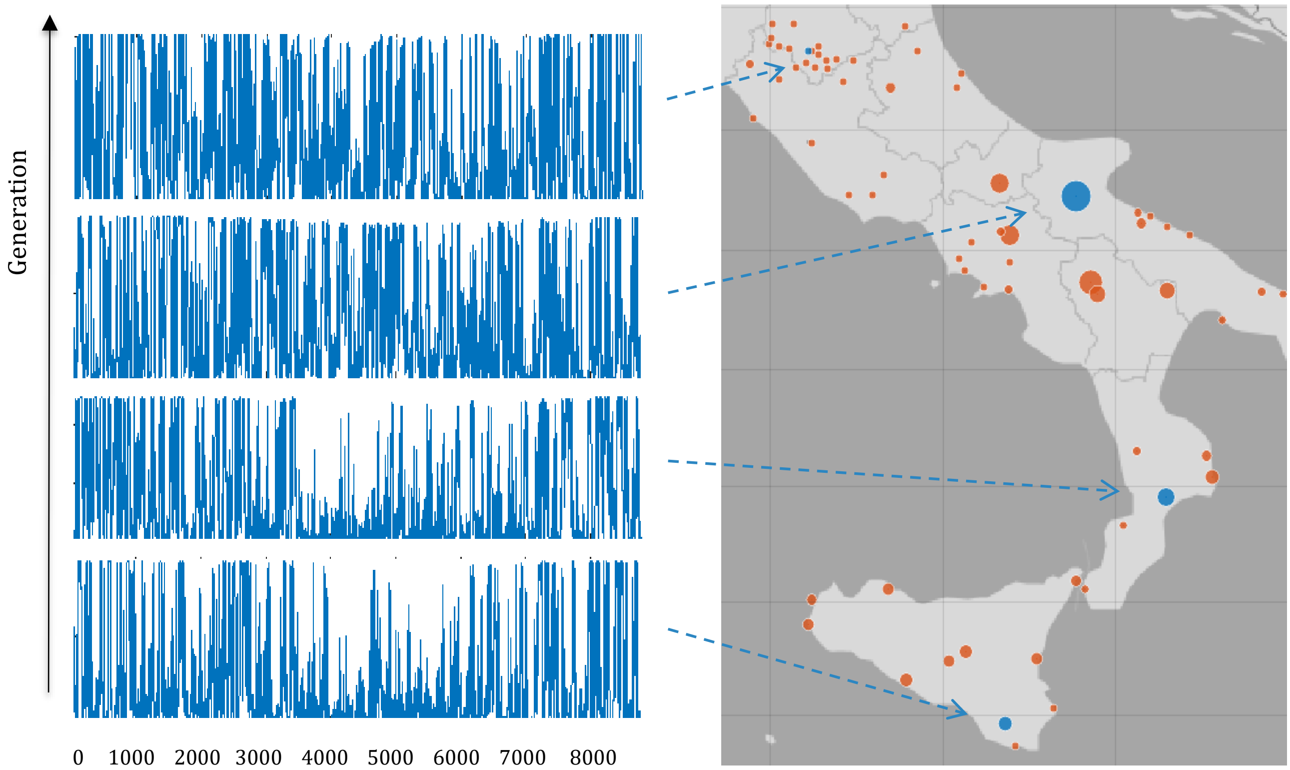


Figure 3-7: Exemplary feed-in time series for wind power in Italy

Standardized power supply of the photovoltaic plant

The standardized feed-in power of a PV plant is calculated on the basis of the time series of the global irradiance at each network node. The global irradiance describes the irradiance on a horizontal surface [20]. Since PV plants are erected at a certain angle of inclination, the irradiance on the module does not correspond to the global irradiance. The conversion is done by breaking down the global irradiance into a direct and a diffuse part. Furthermore, a reflected portion is taken into account. The determination of the direct, diffuse and reflected portion is done according to [20] and is not explained in detail here.

The angle of inclination is assumed to be fix without axis tracking. As the optimal inclination of the PV panel depends on the geographic location, it is varied depending on the latitude.

With the resulting time series of irradiance on the inclined plane $E_{\text{gen}}(t)$ the feed-in power of the PV system is derived according to [20]. For this purpose, the standardized, hourly ideal feed-in is $P_{\text{norm,ideal}}(t)$ calculated.

$$P_{\text{norm,ideal}}(t) = \frac{E_{\text{gen}}(t)}{1000\,\frac{\text{W}}{\text{m}^2}}$$

The ideal hourly feed-in neglects, among other things, power losses due to dirt, snow, shading or efficiency reductions in partial load operation. All these losses are taken into account in the performance ratio PR in summary. According to [20] this is for very good plants $PR = 0{,}8$ and for good investments with $PR = 0{,}75$ while for less efficient plants it can be $PR \leq 0{,}6$. According to [21], PV plants in southern Germany achieve a feed-in of up to 85 % of their nominal capacity in one grid area. The performance ratio is initially neglected at this point, as the losses it depicts are also depicted using a correction factor explained below.

The dependence of the feed-in power on the module temperature is specially taken into account. The module temperature $T_{\mathrm{M}}(t)$ can be calculated from the ambient temperature $T_{\mathrm{U}}(t)$, the irradiance $E_{\mathrm{gen}}(t)$ and a constant of proportionality c according to [20]. The constant of proportionality c depends on the module installation and varies between 22 °C for completely free mounting and up to 55 °C for facade integration without rear ventilation. According to [20] this assumption describes a roof-integrated installation with poor rear ventilation. In [21] this coefficient is taken as the average nominal operating temperature.

$$T_{\mathrm{M}}(t) = T_{\mathrm{U}}(t) + c \cdot \frac{E_{\mathrm{gen}}(t)}{1000\,\frac{\mathrm{W}}{\mathrm{m}^2}}$$

The deviation of the module temperature from the standard test conditions (module temperature 25°C) is used to determine the effect on the performance of the PV system. The power change due to the temperature deviation is described by the temperature change coefficient. According to [20], this is -0.4 % per °C for silicon solar cells. The coefficient of change in output of the PV plant due to the change in module temperature $k_{\mathrm{T}}(t)$ can therefore be described as follows:

$$k_{\mathrm{T}}(t) = -0{,}4\ \%/°\mathrm{C} \cdot (T_{\mathrm{M}}(t) - 25\ °\mathrm{C})$$

This results in the standardized feed-in power of a PV system $P_{\mathrm{norm,real}}(t)$ ultimately as follows:

$$P_{\mathrm{norm,real}}(t) = PR \cdot (1 + k_{\mathrm{T}}(t)) \cdot \frac{E_{\mathrm{gen}}(t)}{1000\ \frac{\mathrm{W}}{\mathrm{m}^2}}$$

Correction factors for wind and photovoltaic plants

If the power supply of all WTGs and PV systems is reproduced for historical years using the methods described above, the calculated energy supply is higher than the real values published in [22] and [23]. This is due to various effects, which have an influence on the power supply and cannot be fully taken into account in the modelling. For example, downtimes due to maintenance, power adjustment due to grid bottlenecks or air turbulence in large wind farms cannot be represented in detail when calculating the feed-in of the WTGs. In the case of PV plants, these include the consequences of pollution, snow, shading or a reduction in efficiency due to partial load operation, as mentioned above. There is also the assumption that the weather data of the COSMO-EU model are above the actual values and the energy supply is thus overestimated (see [24]). For these reasons, the power supply of the plants is adjusted by a correction factor.

The correction factor depends on the selected weather year. A correction factor is determined for each technology for each month of the year. To derive the correction factors, the hourly power supply is determined for all WTGs and PV systems installed according to [25]. This is based on the time series of regional wind speed and global radiation according to the methodology explained above. By balancing the time series of all nodes and integrating the resulting total feed-in time series, the monthly energy supply of the plants is calculated. This energy supply is now compared with the energy actually supplied according to [22].

For PV systems, the correction factor is the ratio of the real injection of all PV plants to the simulated injection of the ideal PV system. In the case of WTGs, the application of the correction factor to the feed-in time series does not make sense, since feed-in peaks would be scaled lower in this case. This would significantly distort the consequences of peak shaving. For this, the correction factor is applied to the wind speed time series. The calculation is carried out iteratively: The correction factor is reduced from 100 % until the simulated energy supply of all plants in the month under consideration corresponds to the real feed-in or, for future scenarios, to the assumed full-use hours.

Standardized demand

Load time series are generated based on national historical load profiles, which are scaled to the target annual consumption, defined by the scenario data. The national time series are spatially distributed to the transmission nodes using regionalization factors as depicted in section 3.2.1.

Standardized power supply of the hydro power plants

As described in section 3.2.1 hydropower plants are distinguished between RoR and reservoir power plants. Due to seasonal variability of rivers, the supply of RoR power plants is quite regular. Hence, the power injection is calculated by means of historical national capacity factors from [26], which are available on an hourly basis. **Figure 3-8** shows exemplary capacity factors for Italy.

$$E_{RoR} = P_{RoR} * CF$$

Reservoir power plants are less weather dependent and can be controlled. It is assumed that they are used to cover the load and thus their generation time series are created proportional to the load.

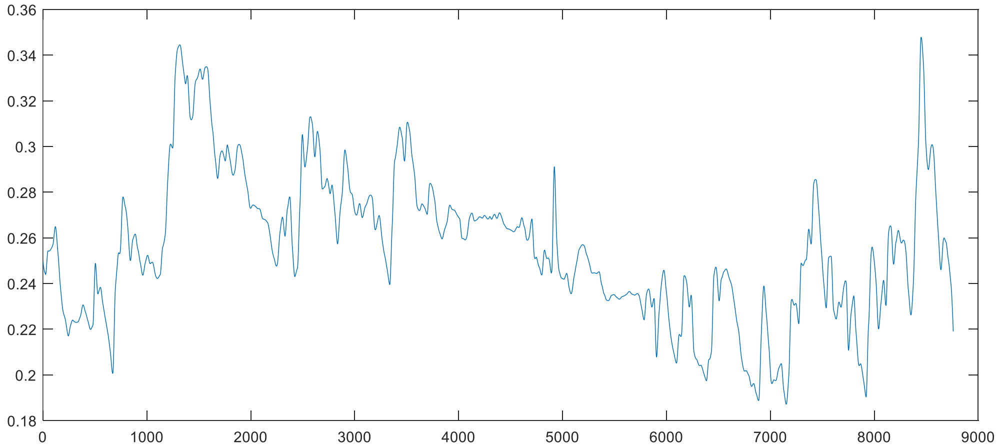


Figure 3-8: Exemplary RoR capacity factors for Italy, data source: [26]

The scenario data only contains information on the sum of full hours of use for both RoR and reservoir power plants (FhU_{sum}), hence, the generated energy has to be divided. For this, at first the sum of the generated energy (E_{sum}) is calculated by multiplying the sum of the installed capacity for both technologies

(P_{sum}) by the full hours of use (FhU_{sum}). The generated energy of reservoir power plants is the difference between the total generated energy and the energy generated by RoR power plants (E_{RoR}).

$$P_{sum} = P_{RoR} + P_{Res}$$

$$E_{sum} = P_{sum} * FhU_{sum}$$

$$E_{Res} = E_{sum} - E_{RoR}$$

Figure 3-9 shows exemplary RoR and Reservoir power plant generation, compared to the load for Italy.

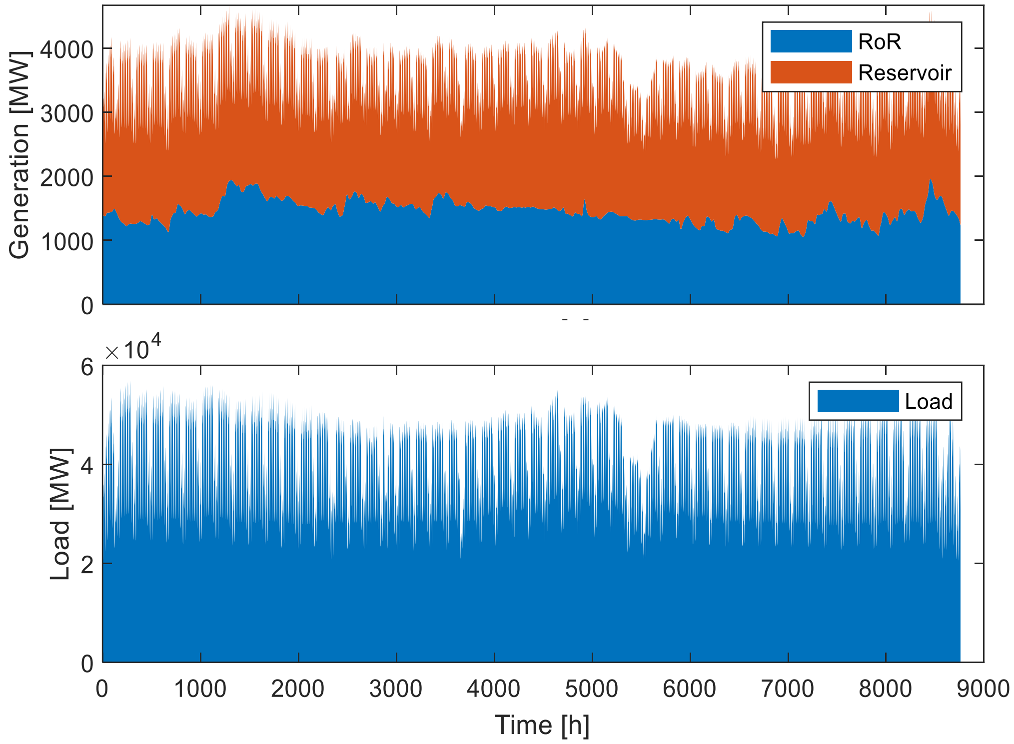


Figure 3-9: Italian time series for hydro generation compared to load

3.3 Market Simulation

The market simulation uses the time series data coming from the regionalization and the scenario data, described in section 3.2.1, as an input. The scenario data includes a power plant database, information on control reserve per country, transmission capacities as well as fuel costs and CO_2 prices. Furthermore, average power plant data i.e. start-up costs, specific emissions and values for up- and downtimes of TTPs are used (see section 3.2.1).

In order to guarantee the compliance between the power plants from the power plant list provided by the regional partners and the scenario data, the data is adjusted first. If power plants for a certain technology are missing in the entire country, these power plants are added. Subsequently the installed capacity is scaled corresponding to the installed capacity predefined by the national scenario data. In addition missing information are complemented by average values. Additional data, i.e. average values for up- and downtimes of TTPs are taken from MAF (see subsection 2.2.1). **Figure 3-10** shows a conceptual block diagram for the inputs and outputs of the market simulation.

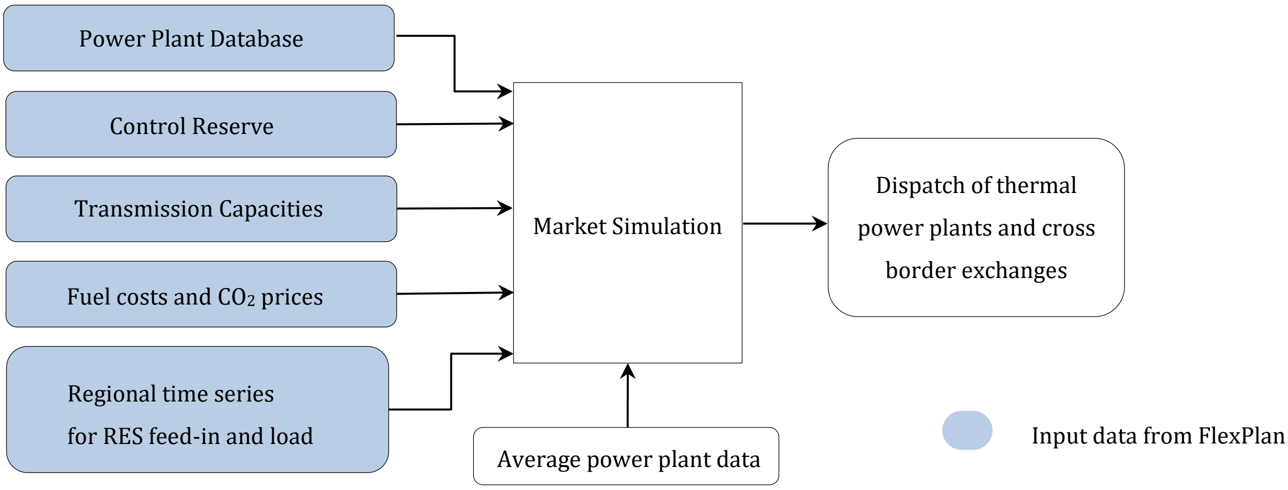


Figure 3-10: Market simulation conceptual block diagram

The power plant deployment optimization is a so-called Security Constrained Unit Commitment Model, which is formulated as a mixed-integer linear program. The optimization aims at determining the cost-minimized use of conventional power plants and storage facilities to cover the electrical load and the reserve power to be maintained, taking into account the RES injection, the available transmission capacities between the market areas and the technical, partly time-coupling restrictions of the generation units and storage facilities.

$$min \sum_{k \in M_t} \left(\sum_{k \in M_k} \left(c_t \cdot P_{k,t} + c_k^{beg} \cdot b_{k,t}^{beg} \right) + \sum_{m_1 \in M_m} \sum_{m_2 \in M_m} c_{m_1,m_2}^{Ex} P_{m_1,m_2,t}^{Ex} \right)$$

The variable generation costs are represented in the objective function for each power plant k in each time step t by the product of the current feed-in capacity $P_{k,t}$ and specific labour costs c_k, which include fuel, CO_2 as well as maintenance and operational costs. Start-up costs are considered by means of the binary variable c_k^{beg}, which is one in the event of the start of the power plant. The trade transaction costs are included in the function by the product of the specific transmission costs between two market areas c_{m_1,m_2}^{Ex} and the export power $P_{m_1,m_2,t}^{Ex}$. The cost data is taken from the scenario data, which is described in section 2.1.

To ensure system stability, a balance between load and generation must be maintained. This balance as well as the provision of controlling power is considered in the form of an additional constraint, which also takes into account possible exchanges with neighboring countries. The total power supply in each market area results from the feed-in capacity of each conventional power plant, the turbine capacity of each PSP and the power supply from RES. The total power demand is composed of the electrical load plus transmission losses and the summed pumping power of PSPs. The transmission capacity between market areas is limited by NTC values. The export and import are determined by the sum of exports and imports between two market areas.

The control reserve is aggregated per market area. For modelling purposes, the difference between the maximum achievable output of power plants and PSPs and the current operating point is calculated for each time step, resulting in the maximum amount available as control reserve. A constraint ensures that the maximum reserve contribution is at least equal to the aggregated reserve requirement. Further technical constraints taken into account include minimum and maximum power, unavailability, minimum downtimes and minimum operating times, power gradients (during operation and during start-up and shut-down processes), maximum turbine and pumping capacities as well as maximum storage capacities.

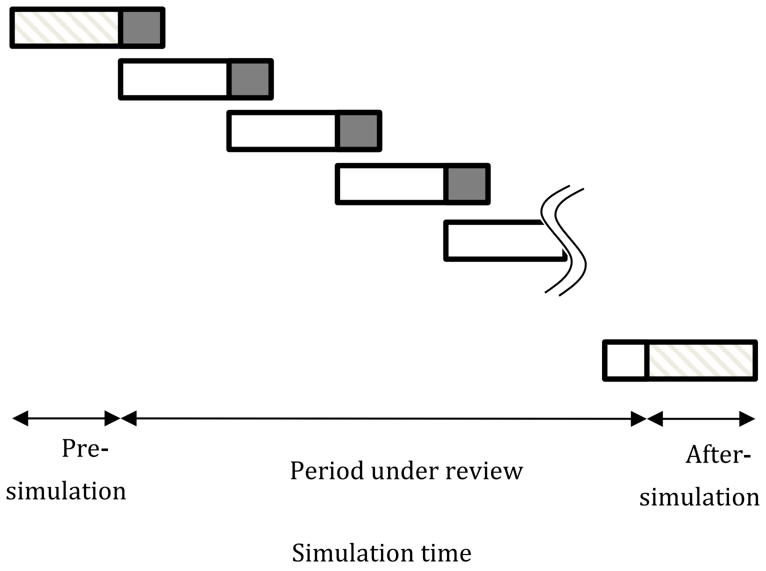


Figure 3-11: Rolling Optimization period

The formulated optimization problem is solved using a rolling approach. For this purpose, the year under consideration is divided into overlapping intervals of constant width, which represent the planning horizons of the market participants. These time intervals are optimized sequentially, whereby the determined system state in a fixed time step of the preceding interval serves as the initial state for the following optimization interval. In addition, a pre-simulation is carried out to generate a steady state of the system directly at the beginning of the year under consideration. The time window simulated for this purpose corresponds to the last time steps of the analyzed year [2].

The optimization provides hourly results for the schedules of conventional power plants and storage facilities as well as trade flows between market areas. **Figure 3-12** shows exemplary results for import and export energy in Germany. As the *MILES* simulation does not only include the countries considered in FlexPlan, there are also exchanges to other adjacent countries.

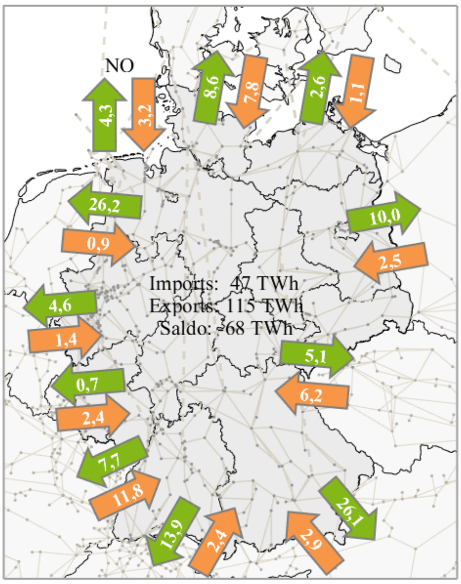


Figure 3-12: Imported and exported energy for Germany

Figure 3-13 presents exemplary market results for Germany. The first two time series show the RES feed-in as well as load and loss time series, which are used as input data for the market simulation. Furthermore, the pumping time series for PSP are included in the figure, as they are also considered as demand. Based on RES and load, the schedules for TPPs and PSP are calculated, as well as the exchange with other countries. Time series for TPPs are depicted in the third part and exchanges in the last part of **Figure 3-13**. The regional time series for RES and load as well as the exchange time series can be considered as the main outputs, thus they will be described in detail in the results (section 4).

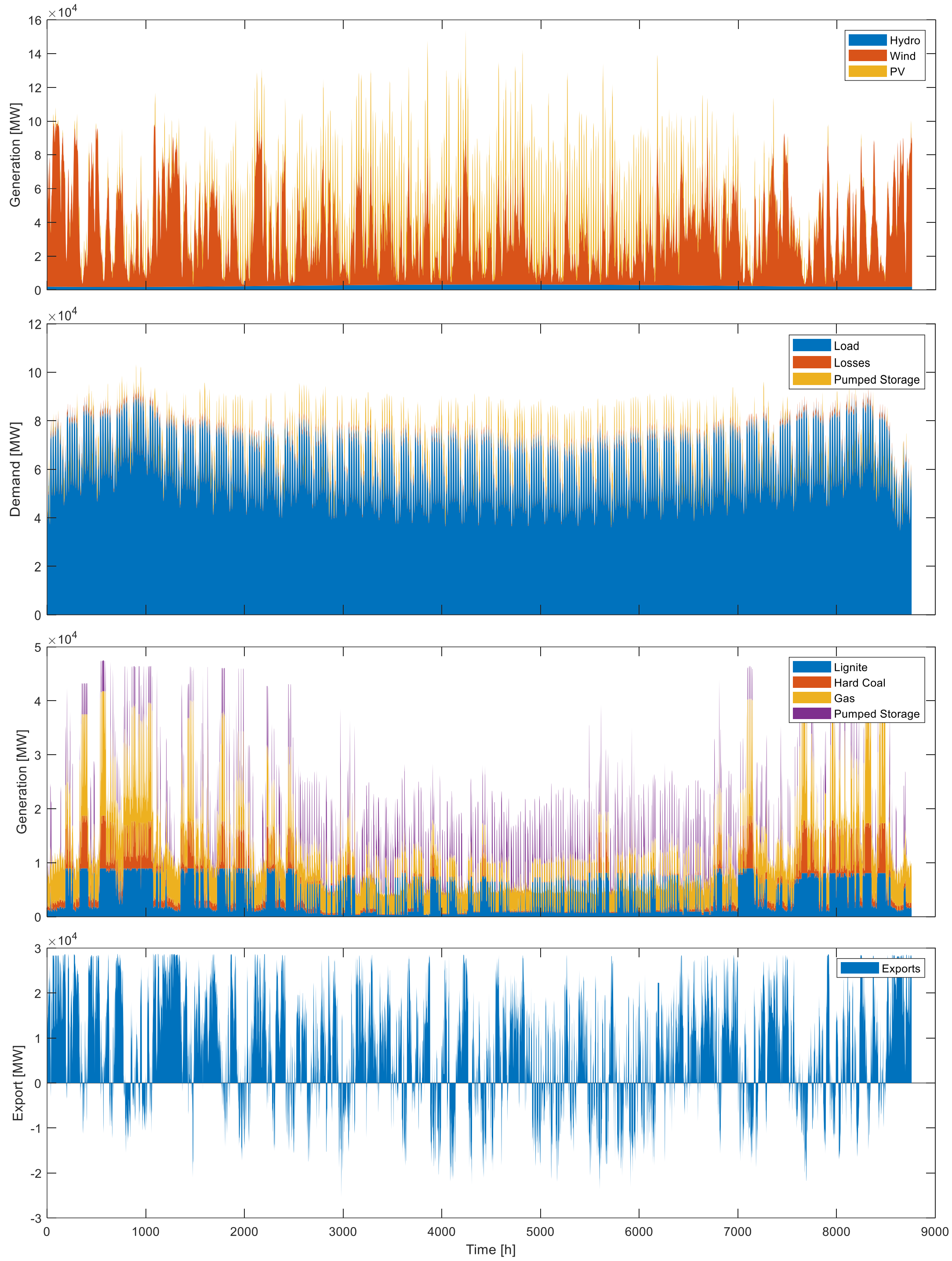


Figure 3-13: Exemplary market results for Germany

4 Results

Applying the regionalization methodology leads to installed capacities for each transmission grid node and RES feed-in time series for each transmission grid node for each hour of the year. In order to present these extensive results comprehensively, the spatial distribution, as well as the time series are summarized for each regional case considering one scenario for the year 2030, shown in the following figures. **Figure**

4-1 and **Figure 4-2** present the spatial distribution. **Figure 4-3** and **Figure 4-4** present the RES time series. **Figure 4-5** depicts export time series for each regional case.

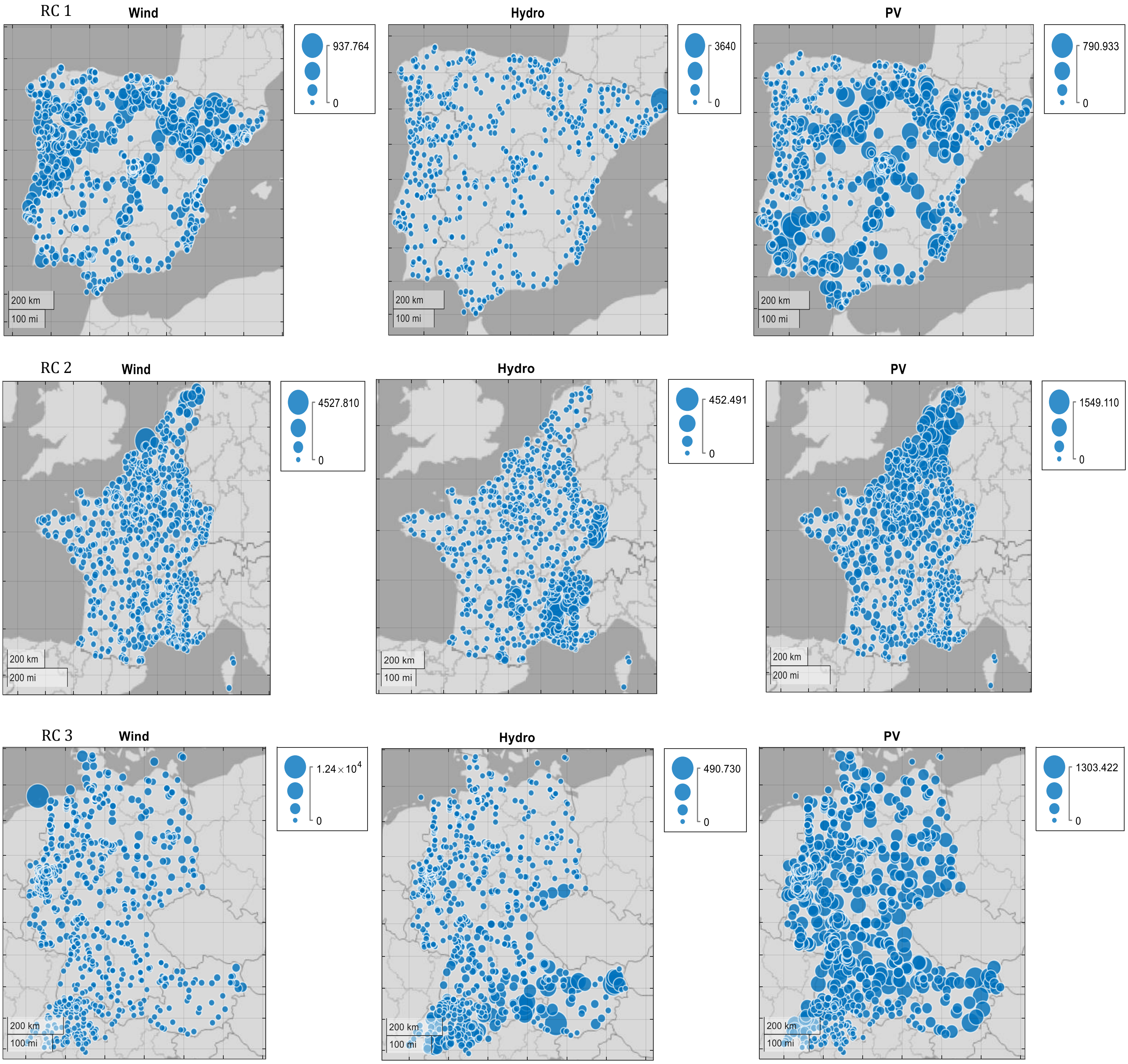


Figure 4-1: Spatial distribution of RES in MW for Regional Cases 1-3

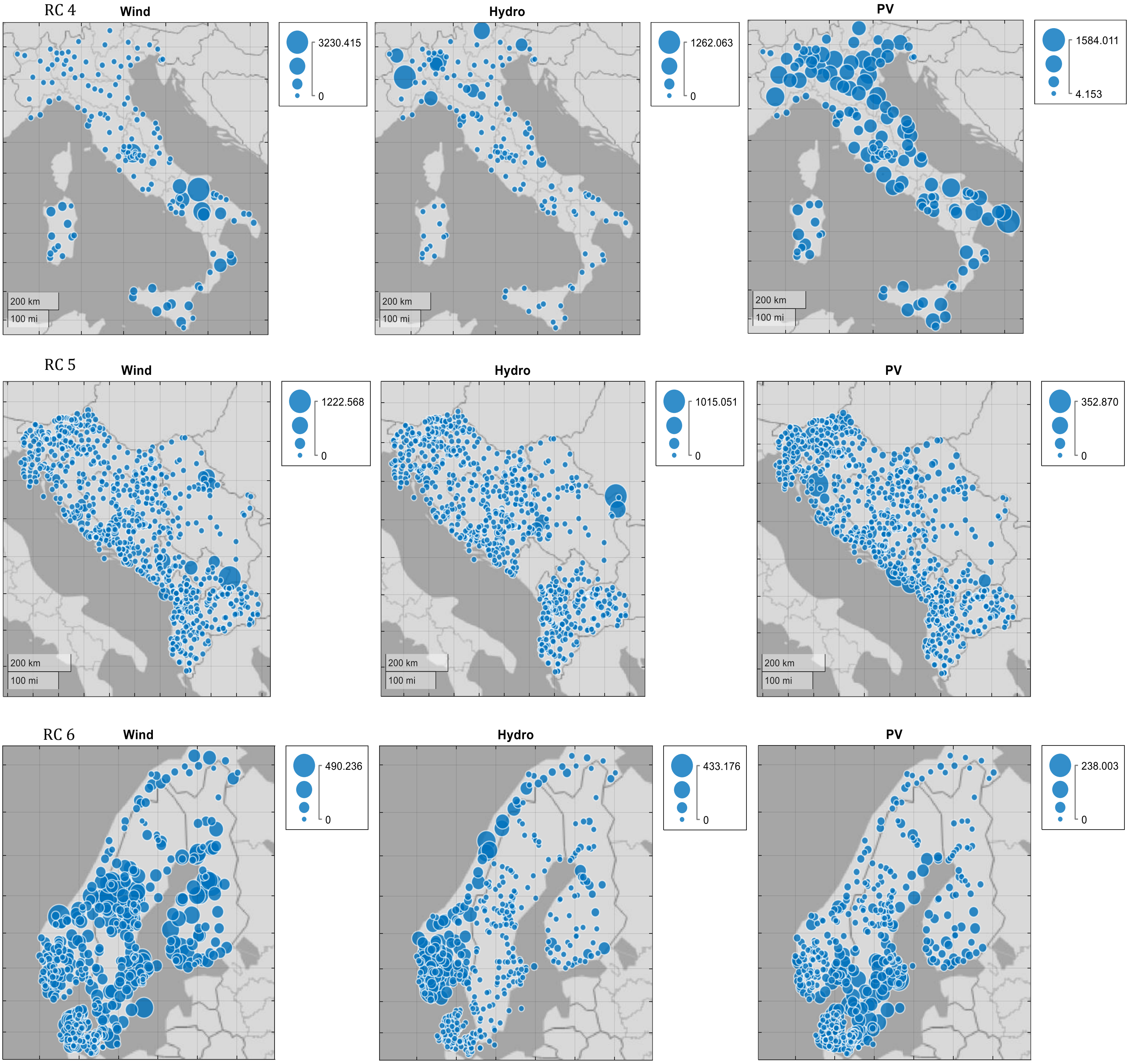


Figure 4-2: Spatial Distribution of RES in MW for Regional Cases 4-6

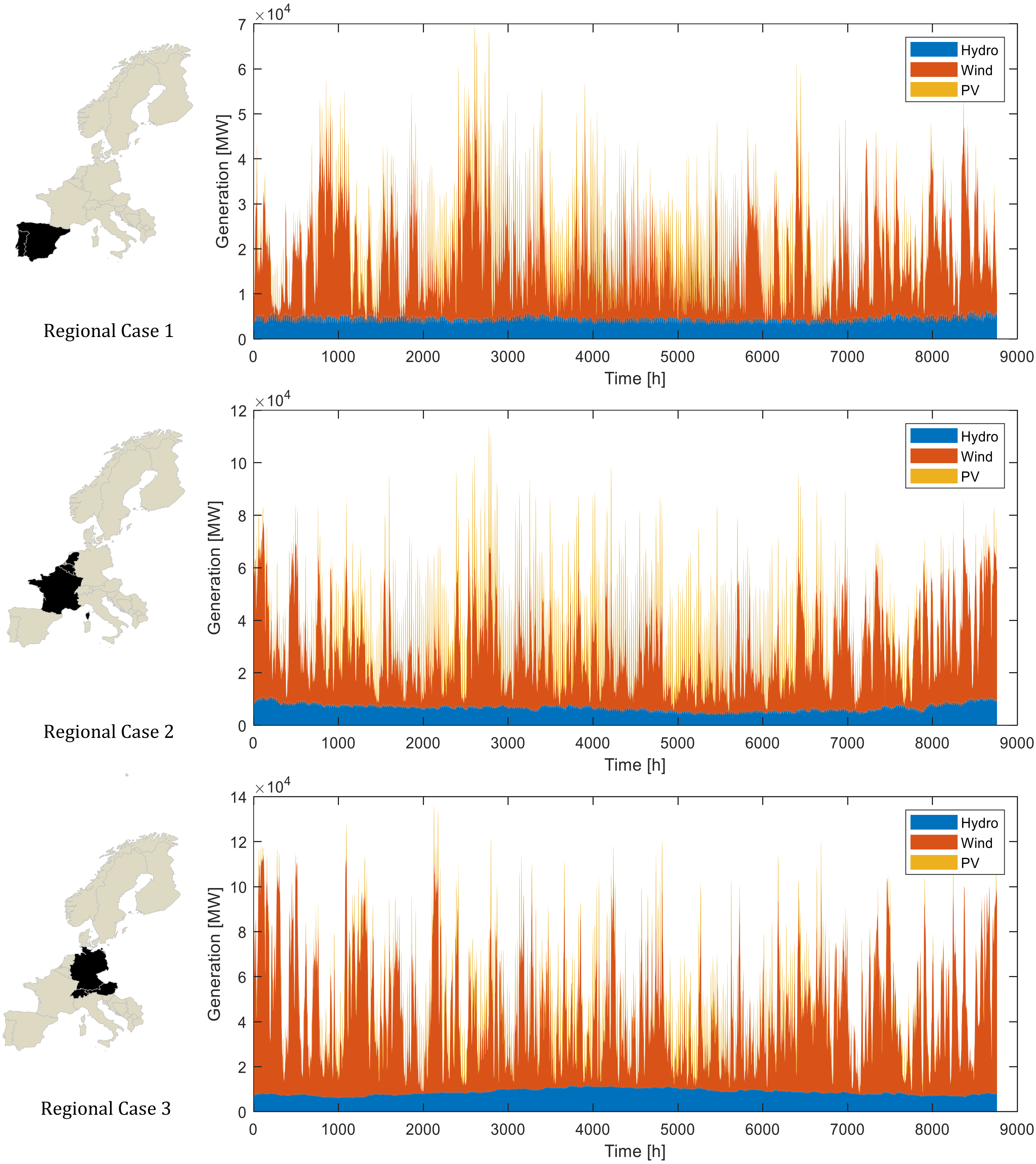


Figure 4-3: RES feed-in time series for regional cases 1-3

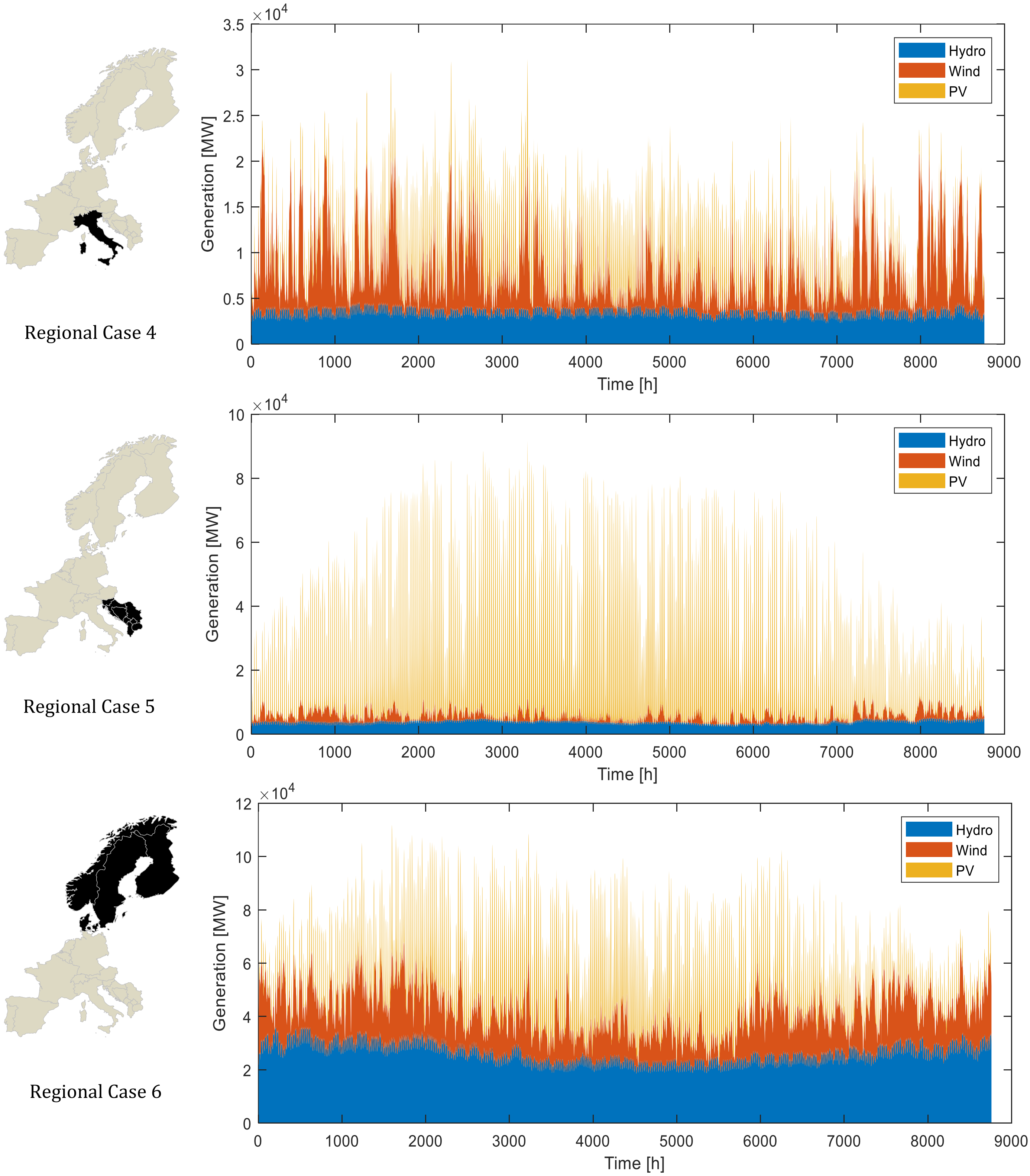


Figure 4-4: RES feed-in time series for regional cases 4-6

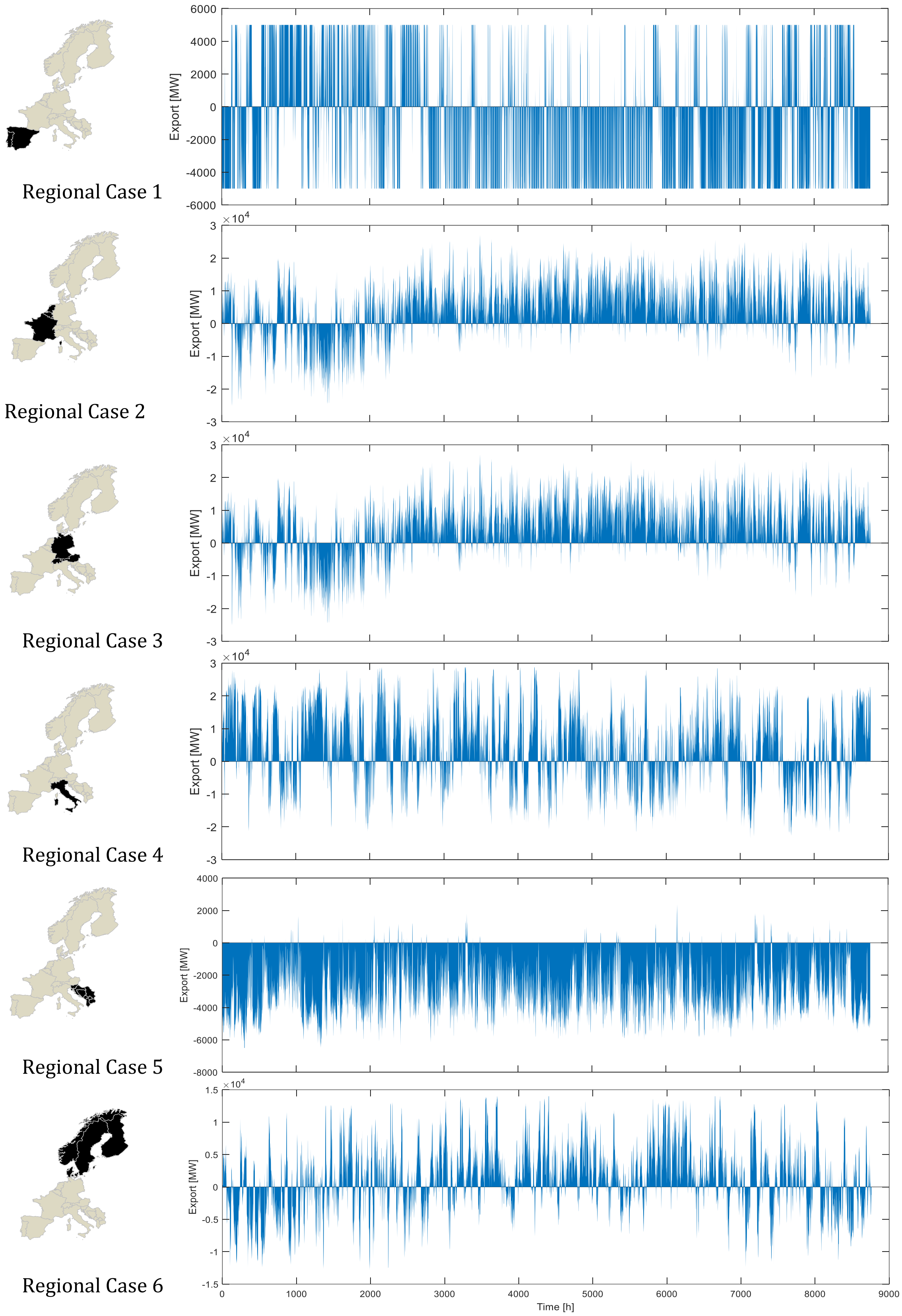


Figure 4-5: Export time series for all regional cases

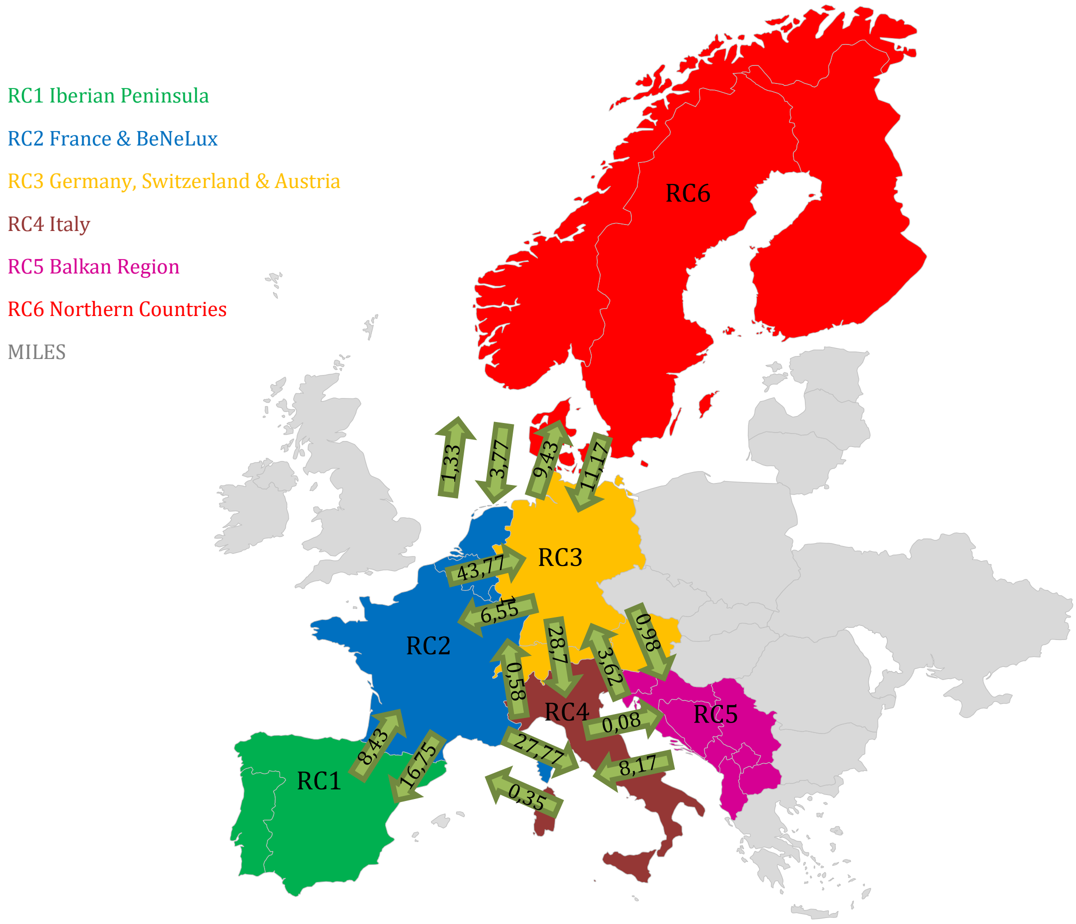


Figure 4-1: Yearly Exchanges between Regional Cases in TWh

5 Conclusions

This document contains the methodology and sample results of the pan-EU simulations executed for three different scenarios for the target years 2030, 2040 and 2050 each, resulting in a set of nine scenarios in total. As FlexPlan aims at developing an innovative grid planning tool, which will be applied to six regional cases, the interconnected EU grid requires a common ground in order to consider continuity and cross border dependencies among the regional cases. For this, a pan-EU simulation is carried out, which is described in this deliverable. The results include on the one hand regional time series for RES and loads, and on the other hand cross border exchanges between the countries.

For the pan-EU simulation, the electricity market and transmission grid simulation framework *MILES* is used and adapted. To distribute installed capacities of RES, a top-down approach is applied. National territory of each country is divided in sub-regions. As the results will be used for grid calculations, the transmission grid nodes are selected as sub-regions. Subsequently various statistical figures for each region are analysed to generate regionalization factors. The considered statistical parameters include socio-structural data, land use, location of existing plants and weather-related data. In a second step feed-in time series are calculated for each region based on historical weather data and the assigned installed capacities. To generate spatially disaggregated time-series of the electrical load, a historical load profile is broken down by means of regionalization factors and scaled to the targeted annual consumption. The market simulation module of *MILES* runs an integrated unit commitment and dispatch model determining power plant and storage schedules as well as cross-border power exchanges between EU countries. For this, the fundamental market model of *MILES* solves a long-term security constrained unit commitment optimization problem. Thereby, the objective aims at minimizing the total variable power generation costs in Europe. The optimal solution is constrained by different technical and economic requirements.

In a nutshell, a pan-EU simulation is carried out, resulting in regional time series as well as cross border exchanges. The regional time series for RES and load, considering weather related variability, are used as an input for the OPF for regional cases. The cross-border exchanges provide a common frame for splitting the pan-EU grid into coherent regional cases. All these data will be combined in the simulation of the six regional cases designed to demonstrate the full capabilities of the FlexPlan grid planning tool.

6 Bibliography

[1] ENTSO-E and ENTSO-G, „TYNDP 2020 - Scenarios Data," 2020.

[2] C. Spieker, Europäische Strommarkt- und Übertragungsnetzsimulation zur techno-ökonomischen Bewertung der Netzentwicklung, Dortmund, 2019.

[3] R. Rodríguez-Sánchez, M. Santos Múgica und S. García Lázaro, „Flexibility elements analysis pre-processor simulation tool," FlexPlan, 2021.

[4] N. Amaro, A. Egorov und G. Migliavacca, „D4.1 Pan-European scenario data," FlexPlan, 2020.

[5] T. Patzwald, B. Matthes und R. D'hust, „Monte Carlo scenario generation and reduction," FlexPlan, 2020.

[6] E. Commission, „A Clean Planet for All - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy," 2018.

[7] F. Gotzens, H. Heinrichs, J. Hörsch und F. Hofmann, „Performing energy modelling exercises in a transparent way - The issue of data quality in power plant databases," 2019.

[8] ENTSO-E, „Mid Term Adequacy Forcast 2020," 2020.

[9] European Environment Agency (EEA), „Copernicus Land Monitoring Service 2018," 2018.

[10] „Eurostat," [Online]. Available: https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat.

[11] Deutscher Wetterdienst, „Regionalmodell COSMO-EU," [Online]. Available: http://www.dwd.de.

[12] V. Liebenau, Einfluss der Regionalisierung Erneuerbarer Energien sowie innovativer Konzepte auf die Netzentwicklungsplanung, Dortmund, 2018.

[13] D. Heinemann, H.-P. Parisi und H. G. Beyer, „Energiemeteorologie," 1999.

[14] E. Hau, Windkraftanlagen. Grundlagen, Technik, Einsatz, Wirtschaftlichkeit, Springer-Verlag Berlin Heidelberg, 4. Auflage, 2008.

[15] g. Gross, T. Frey und P. Trute, „Die Anwendung Numerischer Simulationsmodelle zur Berechnung der lokalen Windverhältnisse in komplexem Gelände," DEWI Magazin, Wilhelmshafen, 2002.

[16] G. Gross und C. Etling, „Numerische simulationsmodelle," Deutscher Wetterdienst, 2003.

[17] Greenpeace, „Renovables 2050, Un informe sobre el potencial de las energias renovables," 2005.

[18] D.E.A. GmbH, „Einführung von Smart Meter in Deutschland. Analyse von Rolloutszenarien und ihrer regulatorischen Implikationen," 2014.

[19] S. Kopp, „Gesammelte Leistungskurven von modernen Windenergieanlagen für Binnenlandstandorte," [Online]. Available: http://www.windenergie-im-binnenland.de/powercurve.php.

[20] V. Quaschning, Understanding Renewable Systems, 2016.

[21] R. Pardatscher, R. Witzmann, G. Wirth, G. Becker, M. Garhamer und J. Brantl., „Untersuchungen zu den Auswirkungen der Photovoltaikeinspeisung auf das Nieder- und Mittelspannungsnetz," VDE ETG Kongress, Würzburg, 2011.

[22] European Energy Exchange AG (Hrsg.), „EEX-Transparenzplattform," [Online]. Available: http://www.eex-transparency.com/.

[23] Bundesministerium für Wirtschaft und Energie, „Zeitreihen zur Entwicklung der EE in Deutschland," [Online]. Available: https://www.erneuerbare-energien.de/EE/Navigation/DE/Service/Erneuerbare_Energien_in_Zahlen/Zeitreihen/zeitreihen.html.

[24] A. Pätzold, Der Vergleich von modellierten Windgeschwindigkeiten mit Produktionsdaten von Windkraftanlagen und die Energieertragsänderung in der Zukunft am Beispiel Windpark Beeskow, Hamburg: Universität Hamburg, 2013.

[25] Netztransparenz.de, „EEG Anlagenstammdaten zur Jahresabrechnung 2016," [Online]. Available: http://www.netztransparenz.de/de/Anlagenstammdaten.html.

[26] M. De Felice, „ENTSO-E Hydropower modelling data (PECD) in CSV format (Version 4)".

[27] Solargis, „Solar resource map," 2019.

7 Annex

Figure 7-1: Legend for CLC data [9]