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Meteorological data for RES-E integration studies

State of the art review

Iratxe GONZALEZ APARICIO
Andreas ZUCKER

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Page 7, WMO 2007, www.wmo.int
Page 8, IPCC 2007, www.ipcc.ch
Page 9, IPCC 2013, www.ipcc-data.org/guidelines

Abstract
The ongoing growth of RES-E requires power system modellers to adapt both methodologies and datasets, in particular time series for electricity generation from wind and PV. Meteorological models are increasingly used for this purpose. This report provides on overview on the methodologies available and the approaches pursued by recent RES-E integration studies. Based on this review, recommendations for best practice are identified.

Title Meteorological data for RES-E integration studies — state of the art review

Contents

1 Introduction

In the European Union, the share of electricity generated from Renewable Energy Sources (RES-E) has grown significantly during the last decade. The European Commission aims at securing this position and "becoming the number one in renewables" [1]. In 2014, the European Council agreed to increase the share of RES total energy supply would increase to at least 27% in 2030 [2]. The electricity sector is expected to make an above average contribution to decarbonisation and RES deployment with a 2030 RES-target of up to 50% of the generated electricity. The very high share of electricity production from wind and solar PV would increase the stochastic nature of the power system.

PV and Wind could become dominant producers during a number of hours of the year while thermal generation would need to provide almost the entire electricity at other moments in time. As a result, thermal generators and other sources of flexibility would be faced with high ramping rates. Wind and PV forecast errors represent an additional challenge of power system with a high RES-E share as these to be taken into account if supply is expected to meet demand at every moment in time.

These challenges require policymakers, system planners and other stakeholders to address basically two issues:

- Revisit rules for ensuring the adequacy of the electricity generation system in the face of a changing supply[1] side.
- Find cost optimal solutions for the integration of RES-E into the power system and market.

Power system models, in particular unit commitment and dispatch models, are widely used tools able to address these issues, yet the emergence of intermittent RES-E has required modellers to adapt both the methodology and the datasets used. Stochastic optimisation using a multitude of scenarios is one example for a methodological improvement found in many recent studies. The successful implementation of modelling approaches for power systems with a high penetration of RES-E crucially depends on the accurate representation of the energy generated by these energy sources.

Two main sources exist for generating RES-E time series required for typical dispatch models: historical measurements of power injected by wind farms or PV panels[2] and power generation time series derived from meteorological variables, i.e. wind speed and irradiation. The latter source of data has the advantage that it can be used for the assessment of RES-E deployment in locations for which no historical measurements exist.

This purpose of this report aims is to provide an overview on current tendencies with respect to the modelling of RES-E as found in recent power system studies. Particular attention is given to the application of meteorological models, originally not widely used by power system modellers. In particular, the report aims at answering the following questions:

- Is there a trend to using meteorological models in power system studies?

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[1] The equally important undergoing changes in the demand side resulting from the electrification of transport (e-vehicles) and heating and cooling are not discussed in this report.

[2] Actually, these time series which are often published by TSOs usually include real time extrapolations that were done with the help of meteorological data.

- How are different types of meteorological models used in power system models?
- Which software tools and datasets are currently available?
- What are the advantages and disadvantages of different meteorological model families?
- Is it yet possible to derive best practices and recommendations for the usage of meteorological models in power system modelling?

2   Meteorological and climate modelling approaches

The generation of electricity from wind farms and solar panels is largely determined by meteorological factors, i.e. wind speed and solar irradiation. Power system and market actors (generators, traders, operators of transport and distributions system, aggregators and prosumers) all require information on both the actual and the expected production of electricity from these sources. This information will typically consist in time series of RES-E production, which are calculated from wind speed and solar irradiation using so called "power curves". The same data (though often with lower temporal resolution) is typically used by energy policy planners for studying transition pathways with the help of energy system models.

Before analysing or modelling the impact of wind and PV on the power system, it is thus important to understand their characteristics, in particular the nature of their variability. From the perspective of a power system modeller (who could possibly also be an actor) this translates into understanding the methodologies and tools to forecast weather parameters and their associated uncertainties. These weather parameters are forecasted by a number of different tools providing data with very diverse characteristics which need to be understood before being used in a power system model. This section describes the basic principles of different tools to obtain the weather data needed for different purposes.

One possible classification of the tools is based on the time frame to be studied. If the RES study is devoted to long-term applications (for example, scenarios up 2050) the data used is increasingly taken from projections derived from *climate models*. Otherwise, for short-term studies (i.e. to study the variability in hours, days, months or a few years) the data comes mainly from the *Numerical Weather Prediction (NWP) models or reanalysis*. Climate and NWP models are techniques based on numerical integration of a set of physical laws. These models are commonly used to forecast weather in terms greater than about 12 h and are used by the NWP operational centres [3]. There is also other type of techniques of weather forecasting based on the *statistical modelling*.

2.1 Climate modelling

The climate is usually defined as the "averaged weather", or more rigorously, as the statistical description in terms of the mean and the variability of relevant quantities over a period of time ranging from months to thousands or millions of years.

Typically, 30-year time interval averages are used to track climate. Those 30 years are called climatological normal, and are considered to be a period long enough to calculate averages that are not influenced by year-to-year variability. In contrast, the weather reflects short-term conditions of the atmosphere. The climate variability is driven by phenomena such as circulations of the lower atmosphere, jet streams, surface ocean currents and the thermohaline circulation [4].

The behaviour of the global climate system is currently simulated by the research community using numerical modelling such as *Global Climate Models (GCMs)*. This approach aims at representing the processes responsible for maintaining the general atmospheric and oceanic circulations and their variability.

However, the human activities increase significantly the complexity of analysing the climate system since this human activity is driven by changes in population dynamics, economic activity, and technological developments. Therefore, in order to tackle this complexity the approach currently used to estimate the *future behaviour of the global*

climate system. It consists in simulating the climate system by means of GCMs together with different assumed techno-economic and demographic scenarios based on Representative Concentration Pathways[3] (RCP) which are derived from scenarios provided by the Intergovernmental Panel on Climate Change[4] (IPCC) (see Table 1 for an overview of the IPCC storylines, IPCC 2007, IPCC 2013).

Although there are many uncertainties associated to those GCMs, they are nevertheless useful tools able to provide relevant insights when carrying out impact assessments. The most recent published studies are collected in the 5th Assessment Report of the IPCC (2014) which presents the reference set of global climate projections for the XXI century. Currently, there are new scenarios developed within IPCC's Coupled Model Intercomparison Project (CMIP5 [5]), published in 2013.

Economic emphasis ⟶

A1 storyline

<u>World</u>: market-oriented
<u>Economy</u>: fastest per capita growth
<u>Population</u>: 2050 peak, then decline
<u>Governance</u>: strong regional interactions; income convergence
<u>Technology</u>: three scenario groups:
• **A1FI**: fossil intensive
• **A1T**: non-fossil energy sources
• **A1B**: balanced across all sources

A2 storyline

<u>World</u>: differentiated
<u>Economy</u>: regionally oriented; lowest per capita growth
<u>Population</u>: continuously increasing
<u>Governance</u>: self-reliance with preservation of local identities
<u>Technology</u>: slowest and most fragmented development

B1 storyline

<u>World</u>: convergent
<u>Economy</u>: service and information based; lower growth than A1
<u>Population</u>: same as A1
<u>Governance</u>: global solutions to economic, social and environmental sustainability
<u>Technology</u>: clean and resource-efficient

B2 storyline

<u>World</u>: local solutions
<u>Economy</u>: intermediate growth
<u>Population</u>: continuously increasing at lower rate than A2
<u>Governance</u>: local and regional solutions to environmental protection and social equity
<u>Technology</u>: more rapid than A2; less rapid, more diverse than A1/B1

Global integration ↑ **Regional emphasis** ↓

⟵ **Environmental emphasis**

Table 1 Summary of the characteristics of the four SRES storylines, IPCC (2007).[5] [6]

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[3] Four RCPs were selected and defined by their total radiative forcing (cumulative measure of human emissions of GHGs from all sources expressed in Watts per square meter) pathway and level by 2100. The RCPs were chosen to represent a broad range of climate (IPCC, 2014). (http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html)

[4] The IPCC is the leading international body for the assessment of climate change. It was established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO) to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts. In the same year, the UN General Assembly endorsed the action by WMO and UNEP in jointly establishing the IPCC.

[5] The four RCP scenarios used in CMIP5 lead to a total radiative forcing (RF) at 2100 that spans a wider range than that estimated for the three Special Report on Emission Scenarios (SRES) scenarios (B1, A1B, A2) used in the Fourth Assessment Report (AR4), RCP2.6 being almost 2 W m−2 lower than SRES B1 by 2100. The magnitude of future aerosol forcing decreases more rapidly in RCP scenarios, reaching lower values than in SRES scenarios through the XXIst century. Carbon dioxide (CO_2) represents about 80-90% of the total human forcing in all RCP scenarios through the century. The ensemble mean total effective RFs at 2100 for CMIP5

However, the spatial (also called horizontal) resolution of GCMs (of about 300 km) is too coarse to represent regional/local heterogeneities, in particular the topography and the water masses. *Regional Climate Models (RCM) and Empirical Statistical Downscaling (ESD)*, applied over a limited area and driven by GCMs can provide information on much smaller scales supporting a more detailed impact and adaptation assessment and planning, which is vital in many vulnerable regions of the world.

Simulations with RCMs driven by GCMs (with a resolution of about 25-50 km) have been carried out; especially for Europe (e.g. PRUDENCE [7] – from 2001 to 2004 –, ENSEMBLES [8]– from 2004 to 2009 – and CORDEX [9] EU projects –started in 2009). Furthermore, downscaling/regionalisation techniques are applied to GCMs and RCMs in order to provide a more detailed output for impact assessment studies at the regional and local levels (about 12 km or less).

Figure 1 shows an example of the difference in the horizontal resolution between a GCM, named HadAM3H, and an RCM, named RegCM [10]. The diagrams show the distribution of temperatures across Europe at 100 km (left diagram) and at 50 km (right diagram) resolution. These distributions are frequently needed for power system studies as temperature is a key variable for determining the demand for electricity (in particular for heating and cooling[6]). It can be seen from **Figure 1** that if the working domain stretches over a large region characterised by a complex orography, using the temperature data of a 100km resolution can produce significantly different results than using data of a 50 km resolution.
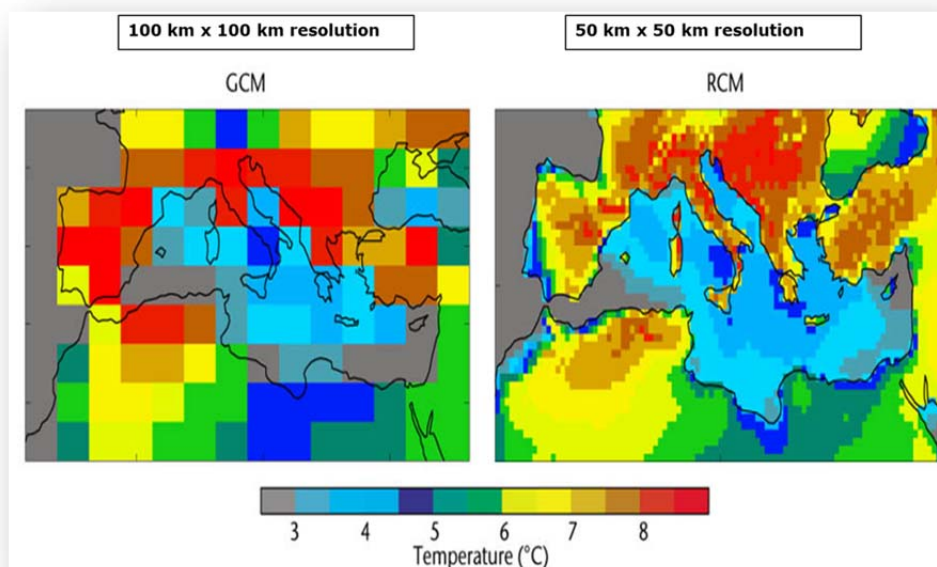
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concentration- driven projections are 2.2, 3.8, 4.8 and 7.6 W m−2 for RCP2.6, RCP4.5, RCP6.0 and RCP8.5 respectively, relative to about 1850, and are close to corresponding Integrated Assessment Model (IAM)-based estimates (2.4, 4.0, 5.2 and 8.0 W m−2).

[6] E.g. in France, electricity demand increases by 2400 MW with every drop of temperature by 1 degree C [11].

When focusing on a specific area, regionalisation techniques are usually applied in order to capture the effect of fine-scale forcing (Figure 2); in particular in areas characterised by fine spatial variability of features such as rugged topography and very diverse land surface conditions. A series of downscaling approaches can be used. These fall into two categories: process-based techniques, involving the explicit solving of the physical dynamics of the system (so-called dynamical downscaling), and empirical methods that use identified relationships derived from observational data. An overview of the downscaling techniques can be found in [12], [13].
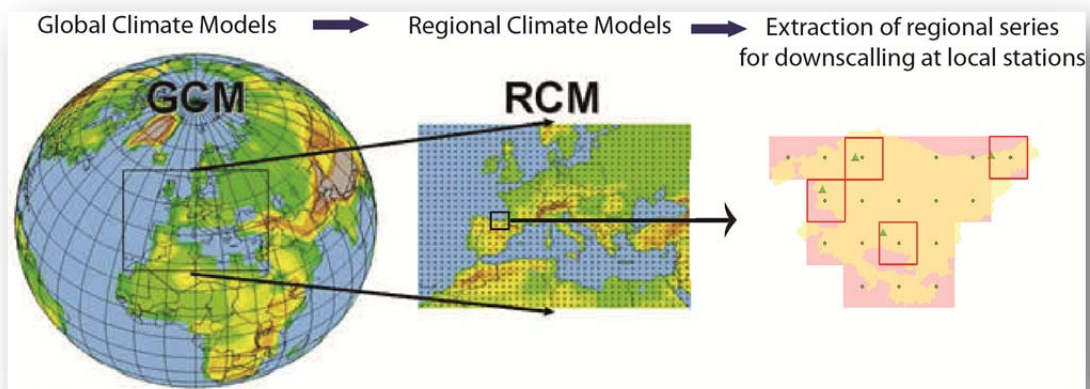
Figure 2 Downscaling from Global Climate Models (GCMs) to Regional Climate Models (RCMs) and extraction of the regional time series to capture the effect of the specific variable of the finer scale at specific location [14]

It is important to take into account that, although a finer spatial resolution gives more accurate results, in some cases it adds an extra factor to the uncertainty cascade, that is, the progressive accumulation of all sources of uncertainty (see Figure 3). The uncertainty cascade results from combining the uncertainty related to physical, economic, social, and political impacts and policy responses.

One part of the uncertainty cascade arises when feeding an RCM with data originating from a GCM. The uncertainty associated to the unpredictability of the global climate system is dealt with by using multiple forcing GCMs. The deficiencies of RCMs can be tackled by using an ensemble of RCMs. In addition, the outputs of climate models and downscaling techniques have to be compared with observations during a reference period. Thereby, the goodness of fit (bias) that summarises the discrepancy between the observations and the model outputs is evaluated before analysing future climatic scenarios generated by such models.
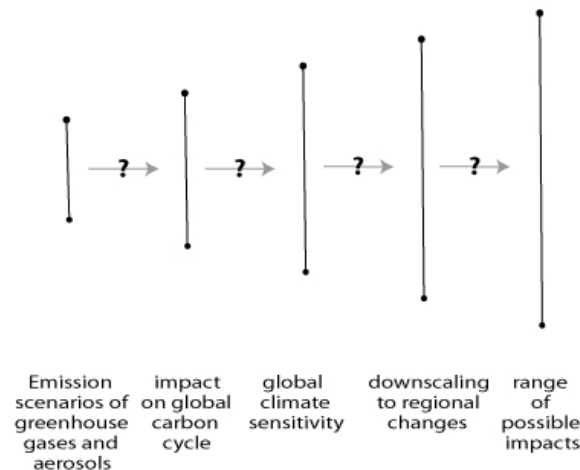
2.2 Numerical Weather Prediction (NWP) models

Meso scale meteorological models are N*umerical Weather Prediction (NWP) and research models* able to simulate atmospheric processes on a spatial scale from 20 to 1000 km and resolve temporal fluctuations lasting from 1 to 12 hours [15].

Those models solve the equations describing the physical atmospheric processes and how the structure of the atmosphere changes within this time interval. The principal equations relative to the motion on the atmosphere (called primitive equations) are Newton's second law of motion (momentum conservation), the first law of thermodynamics (energy conservation), the continuity equation (mass conservation), the equation of state and the water conservation equation [16]. Those equations are simplifications of the actual physical processes taking place in the atmosphere. Due to their nonlinearity, solutions are computationally expensive to find and, therefore, numerical approximations are applied [17].

Additionally, current weather observations serve as input to the numerical computer models through a process known as *data assimilation* to produce outputs of temperature, precipitation, wind speeds and hundreds of other meteorological elements from the oceans to the top of the atmosphere.

Other common tool used to generate weather data and frequently used by the energy community is the *reanalysis*. The reanalysis integrates a variety of observing systems with numerical models to produce a temporally and spatially consistent synthesis of observations and analyses of variables not easily observed. The one component of this framework which does vary is the sources of the raw input data. This is unavoidable due to the ever changing observational network which includes, but is not limited to, radiosonde, satellite, buoy, aircraft and ship reports. Currently, approximately 7-9 million observations are ingested at each time step.

2.2.1 NWP model configuration

NWP models divide the atmosphere into 3D cubes (**Figure 4**). Grid points are centred in the middle of the cube. NWP solves weather parameter equations for each atmospheric variable at each grid point. The forecasted value represents the grid box area average. The minimum distance between adjacent grid points defines the horizontal model resolution. Higher resolution (more and closer grid points) models are more accurate than lower resolution models but computationally more expensive.
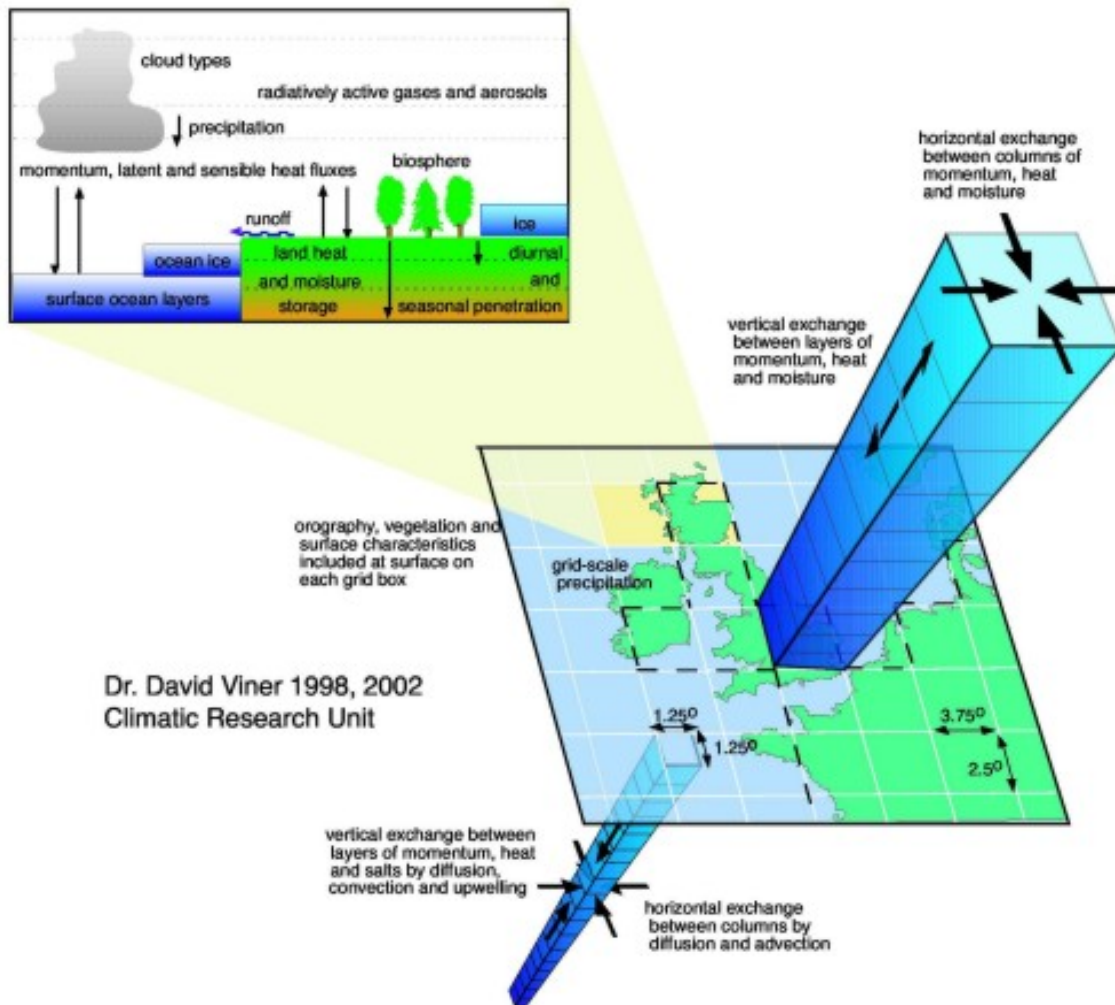
Figure 4: 3D cubes of a model representing one cell of the grid[18]

Another important issue in the model configuration is the representation of the orography[7] which is limited by the resolution of the terrain dataset. If the terrain dataset is coarse, it cannot provide details about the orography needed by a high-resolution model. Due to grid point averaging, elevations of the highest mountain peaks are generally lower in the model than in reality and valleys are often not represented in the models or are represented with less elevation difference between peaks and valley floors. This implies that orographic influence features such as convection and downslope wind will not be fully depicted by the model with a coarse resolution [17, p. -]. As a consequence, the wind speed data series

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[7] Orography is defined as the discipline studying the topographic relief of mountains.

obtained from such models would not capture the strong wind fluctuations (where are the best places to allocate wind farms). The error will propagate into time series representing the power generation of wind farms.

The horizontal spatial resolution varies from about 15 km to less than 1 km; however, there are atmospheric processes (e.g. Atmospheric Boundary Layer (ABL) turbulence and convective mixing) that cannot be explicitly represented by these models and must be parameterised. For example, a proper parameterisation of the ABL physics is important for modelling the formation of air masses, wind profiles, temperature and humidity in the lower atmosphere, boundary layer clouds, forecast parameters at 2 m height and fog and dew/frost formation. For resolutions below 1 km, meso-scale models usually require additional parameterization schemes of the turbulence at finer scales [19] or micro-scale flow models.

NWP models divide the atmosphere vertically into layers to depict the weather phenomena. The higher the number of vertical layers, the better chance to depict the weather phenomena but also more computational power is needed. Increasing the vertical resolution in the lower atmosphere enables the models to better define boundary layer processes and features that contribute significantly to sensible weather elements, such as low level winds, turbulence, temperature, and stability.

2.2.2 Types of models

Based on the representation of vertical movements there are two types of models:

the *hydrostatic models* which assume hydrostatic equilibrium, that is, the weight of the atmosphere, which exerts downward pressure, is in equilibrium with the strength of the pressure gradient, which exerts upward pressure [19]. Therefore, the hydrostatic models can only simulate the meteorological phenomena resulting from hydrostatic and vertical changes.

The *non-hydrostatic models* include equations for representing dynamics of the vertical movements and can simulate directly the time of these processes provoked by the hydrostatic and vertical changes. Hydrostatic and non-hydrostatic models use different approaches for simulating acoustic waves.

Acoustic waves propagate in the atmosphere with high speed (so they would need fine time-steps to be solved, slowing down the simulation) but have a low impact on the meteorological variables. Therefore numerical processing is applied to filter or treat those waves. Hydrostatic models completely filter the acoustic waves. Non-hydrostatic models can resolve these effects by means of different approaches [20]:

- Models can use anelastic approximation which consists of removing the sounds waves from the atmosphere assuming the conservation of mass. Here, the model cannot express the variation of the horizontal mean pressure and removes the thermal expansion of the air. However, the anelastic approximation is available for most of the models and has been widely used in several research models due to its computational robustness

- Models can also keep the fully compressible formulation and apply numerical techniques. There are two options to resolve: the *semi-implicit approximation* which

reduces the speed of the fast wave and the *split explicit techniques* which make a separation between the fast and slow waves.

There are many meso meteorological models in use for NWP and research at operational centres of national meteorological services [20], among which the following can be highlighted: the hydrostatic models *HIRLAM* (High Resolution Limited Area Model) [21] and *ALADIN* (Aire Limitée Adaptation Dynamique Développement Inter-National) [22] are commonly used in Europe. There also exist non-hydrostatic versions of these models: *HIRLAM-NH* [21] and *NH ALADIN*. Examples for non-hydrostatic models used by NWP operational centres are *WRF* (Weather and Research Forecast) [23] which is a split explicit model and *UKMO* (UK Met Office) [24]. *COSMO-EU* is a meso scale model, formerly known as LME. Together with the global model GME and the convection-resolving model COSMO-DE (for Germany) it forms the core of the German meteorological Agency's Numerical Weather Prediction (NWP) system[8].

2.2.3 Uncertainties associated to the NWP models 'configuration

Depending on the configuration of the model data can be obtained at different spatial resolutions. Higher resolution model configurations are more accurate but the computational resources are also higher. As explained above, the model resolution critically depends on the representation of terrain orography in the model

Horizontal resolution

The example in **Figure 5** shows results for the Basque Country obtained by the HIRLAM model for different spatial resolutions. The region in the north of the Iberian Peninsula is, characterised by a coastal and complex terrain. It can be seen that only the highest resolution (right column) is able to capture the turbulences due to the terrain. The effect is relevant if a difference of 4 m s^{-1} in the wind speed or 3 degrees in temperature is significant, this is usually the case for power system studies.

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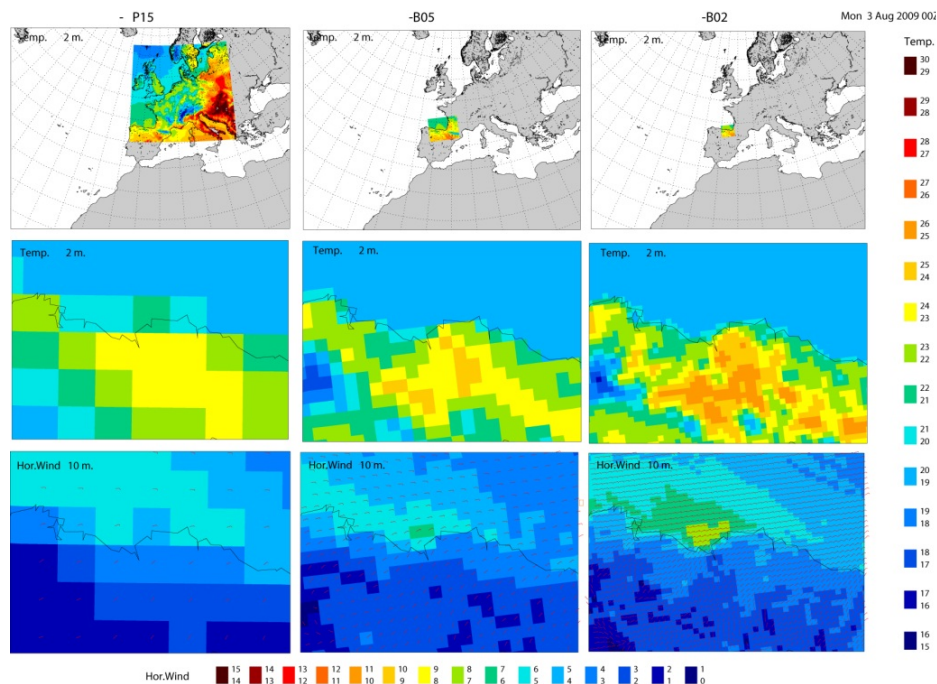
[8] http://www.cosmo-model.org/content/tasks/operational/dwd/default_eu.htm

Model levels

Other additional characteristics of the data to take into consideration are the height at which the variable is calculated since at different heights the atmosphere has different dynamics (**Figure 6**). For example, wind speeds are often taken at 10 m height and then extrapolated logarithmically to other heights [25].

NWP models solve the weather element equations for each vertical layer of the atmosphere and several layers at different altitudes can be selected to investigate the wind potential energy.
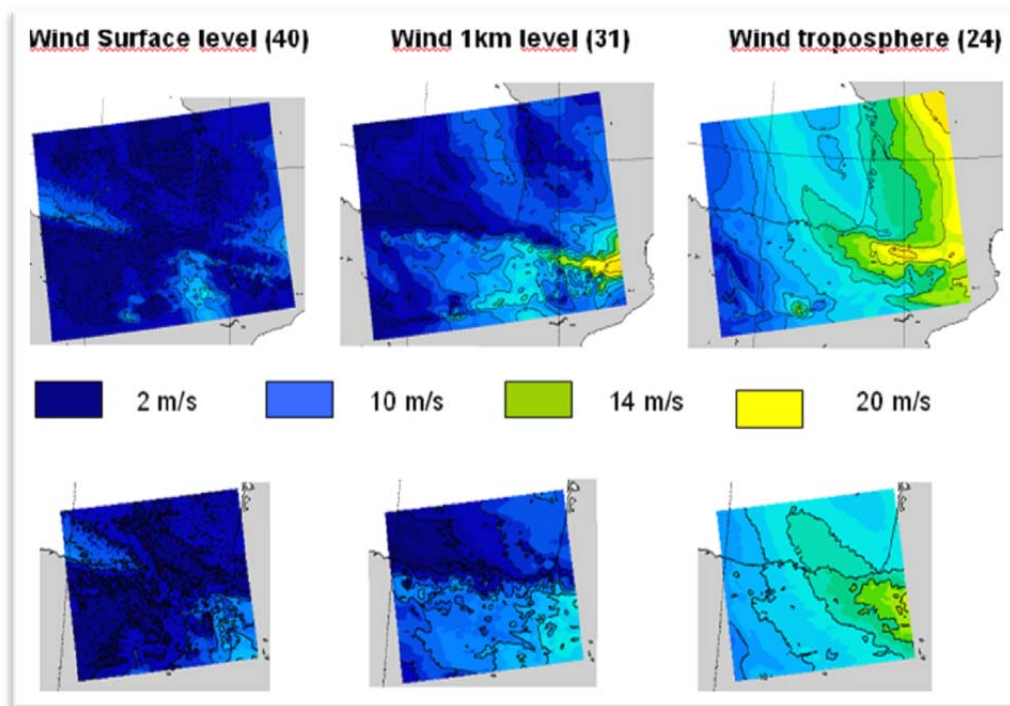
Figure 6 **Wind speed at different vertical layers of the model and at different horizontal resolutions performed by the HIRLAM model** [14]

2.3 Statistical modelling

"*A statistical model is a probability distribution constructed to enable inferences to be drawn or decisions made from data*" [26].

For weather forecasting, the prognostic equations are developed by statistical analysis of a sufficiently large learning data sample (training period) collected from monitoring stations. The weather elements forecasted by statistical methods typically include site-specific weather conditions (e.g., maximum and minimum surface temperature, cloudiness, visibility, fog occurrence, precipitation amount, occurrence and type, thunderstorm occurrence and severity, clear-air turbulence, surface air quality, local winds). Those variables representing the weather elements to be forecasted are called *predictands*, and the variables the forecast is based on are called *predictors*. The definition of the predictand should reflect:

i. The nature of the weather/pollutant element,
ii. The distribution of observations (climatology/air pollution) of the element, and
iii. The user requirement.

Concerning choice of the predictors, it is advantageous to comprise as much as possible information in the lowest number of physically reasonable predictors. This makes the prognostic equations more stable. The dependence of the predictand on the predictors is expressed in terms of the prognostic function which is to be determined from a training period. The learning sample consists of the previously observed values of both predictand and predictors. In order to obtain a serviceable prognostic function; the training period should be representative and as large as possible.

Statistical models are not considered deterministic models, in the sense that they do not establish nor simulate a causal, physical relationship of the atmospheric processes. They establish a relationship between the predictors and predictands without detailing the causes and effects. The most often used statistical models for meteorological (and also air quality forecasting can be classified into three main families:

Models based on *time series analysis* [27], [28]; which account for the fact that data points taken over time may have an internal structure (such as autocorrelation, trend or seasonal variation) (e.g. ARIMA [29]. Multivariate models [30].

The *multiple linear regression-based models* (MLR) [31], [32] which attempt to model the relationship between two or more explanatory variables and a response variable by fitting a linear equation to observed data. MLR models have a large variety of extensions which allow some or all of the assumptions underlying the basic model to be relaxed (e.g. Generalised Linear Models [33]; Heteroskedastic Models [34]; Hierarchical Linear Models [35].

Finally, *neural network-based models* [36], [37] which are composed of a large number of highly interconnected processing elements (neurones) working in unison to solve specific problems.

Statistical analysis is used in combination with the NWPs through the *Model Output Statistics* (MOS). The MOS approach is a technique to interpret numerical weather prediction model outputs. It is frequently used to improve the model forecasts. Another reason to apply statistical post-processing is to scale down NWP output, typically rather coarse in temporal and spatial resolution, to finer local and temporal levels. The biases introduced in this procedure can then partly be handled by applying statistical corrections.

3 Main sources to obtain weather data for energy and power system studies

Recently, the interest of power system modellers in sources for weather data generation has been grown. There are different approaches to obtain the weather data for different applications involving RES-E studies. In this context, the main data used are:

- Wind speed in order to calculate the wind power production.
- Solar irradiation in order to calculate the solar PV production.
- Temperature to assess demand profiles.
- Precipitation for using in hydropower production and reservoirs levels purposes.

This report focuses on wind and solar irradiation data and the next section summarizes the sources to obtain such data.

3.1 Numerical Weather Prediction, data assimilation and reanalysis

3.1.1 European Centre for Medium-Range Weather Forecast (ECMWF)

- *ERA-40:* ERA-40 is a 45-year global atmospheric reanalysis for the period 1 September 1957 – 31 August 2002. It was produced using the Ensemble Prediction System (IFS Cy23r4) [30] and completed in April 2003, with a horizontal resolution of 125 km approximately and 60 vertical layers at 6-hourly atmospheric fields [39].
- *ERA-interim:* ERA-Interim is the latest global atmospheric reanalysis produced by the ECMWF. The ERA-Interim project was conducted in part to prepare for a new atmospheric reanalysis to replace ERA-40, which will extend back to the early part of the twentieth century. ERA-Interim covers the period from 1 January 1989 onwards, and continues to be extended forward in near-real time. An extension from 1979 to 1989 is currently in preparation. Gridded data products include a large variety of 3-hourly surface parameters, describing weather as well as ocean-wave and land-surface conditions, and 6-hourly upper-air parameters covering the troposphere and stratosphere vertical integrals of atmospheric fluxes, monthly averages for many of the parameters, and other derived fields have also been produced [40].
- *100m height wind data set:* Analyses/forecasts covering the whole Earth providing an hourly basis for the period 2012-2014 and interpolate the 100 m wind vertically from the two nearest model levels, with a horizontal grid spacing of about 16 km. However, this product is not freely available and requires the access to the ECWMF archives.

3.1.2 National Oceanic and atmospheric administration (NOAA)

- *Reanalysis-1* (NCEP/NCAR) and *reanalysis-2* (NCEP/DOE) [41]: these datasets represent a global reanalyses of atmospheric data spanning 1948 (NCEP1) and 1979 (NCEPII) to the present at a 1.875 degrees horizontal resolution. The temporal resolution is 6-hourly and includes different layer heights [42].

- *Climate Forecast System Version* (1 and 2) [43]: – CFSR and CFSRv2. It is a coupled model, composed of four separate models (an atmosphere model, an ocean model, a land/soil model, and a sea ice model), which work together to provide an accurate picture of weather conditions. This model offers 6-hourly data with a horizontal resolution down to 0.3 degree for a period from 1979 – 2011 (CSF Reanalysis) and 2011-present (CSFRv2) [44].

3.1.3 National Aeronautics and Space Administration (NASA)

- *MERRA* [45]: This dataset is a reanalysis using a major new version of satellites: the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). The Global Modelling and Assimilation Office (GMAO) [46] has used its GEOS-5 atmospheric data assimilation system (ADAS) to synthesise the various observations collected over the satellite era into an analysis that is as consistent as possible over time because it uses a fixed assimilation system. The analysis covers a period from 1979 to the present. The products are generated on three horizontal grids: Native (0.5 x 0.66 degrees using model conventions) and Reduced (0.25 x 0.25 degrees). The native time resolution for the 3-D diagnostic fields is 3-hourly and the 2-D diagnostic fields are in 1-hourly resolution.

3.2 Climate projections

As described in the introduction, a "climate normal" is by definition representative for several decades in the past or in the present (frequently use as minimum 30 years) while a "projection" looks into the future within the same period window.

Thus, a *climate projection* is usually a statement about the likelihood that climate will be altered several decades to centuries in the future if certain influential conditions develop with respect to the present. In contrast to a prediction, a projection specifically allows for significant changes in the set of boundary conditions, such as an increase in greenhouse gases, which might influence the future climate. For projections extending well out into the future, scenarios are developed of what could happen given various assumptions and judgments [47]. Therefore, climate data need to be handling as statistical probabilities and trends and not in absolute terms as the meteorological data provided by the NWP models. The output of the climate models has been recently used for RES-integration studies such as in [48]. Data for Europe can be found in the following sources:

3.2.1 *CMIP5* – Coupled Model Intercomparison Project Phase 5

CMIP provides a community-based infrastructure in support of climate model diagnosis, validation, inter-comparison, documentation and data access. This framework enables a diverse community of scientists to analyse GCMs in a systematic fashion, a process which serves to facilitate model improvement.

3.2.2 *CORDEX–* Coordinated Regional climate Downscaling Experiment

This project [9] provides global coordination of Regional Climate Downscaling for improved regional climate change adaptation and impact assessment. For Europe already coordinated ensembles[9] of regional climate simulations at rather high spatial resolution exist (Ensembles, Prudence). These climate scenarios were provided on grid-sizes down to 25 km and are based on the previous generation of emission scenarios (IPCC). In order to proceed from this point, the EURO-CORDEX simulations will not only consider the new RCP scenarios, but also increase spatial resolution. EURO-CORDEX simulations will focus on grid-sizes of about 12 km. Auxiliary simulations with the standard CORDEX resolution of about 50 km are being conducted additionally.

3.2.3 *NOAA:* CM2 Global coupled climate models (CM2.X)

The CM2 Global Coupled Climate Models [49] (CM2.X) provides datasets showing general climate conditions during the 20th century and projections into the 21st century based on various climate scenarios. The two models were run under different conditions set by the 2007 IPCC to study the general pattern of warming in the 20th century. Atmospheric gases and solar irradiance values from 1861 to 2000 helped produce a suite of atmospheric, ocean, land, and sea ice gridded data.

3.3 Uncertainties associated to the RES-E data derived from weather data selection

One of the main issues that must to be considered is the associated weather uncertainties when selecting weather data for the generation of RES-E generation time series. There are different sources contributing to the cascade of uncertainties when transforming a meteorological variable into the corresponding wind or solar power generation. To deal and reduce the uncertainties, the studies identified in the literature aim at either:

- Developing more accurate numerical and statistical solar/wind power forecasting techniques or,
- Studying the Solar/Wind Power Forecasting Error (S/WPFE) as a single probability density function, describing the error variability as a range from the lowest to the highest value of the distribution in the historical records.

Among all RES-E, wind power forecasts have the highest uncertainties mainly due to the temporal and spatial variability and predictability of the wind field (See **Figure 7**). In *studies of the first category*, a cascade of uncertainties emerges from different parts of the methodology and tools applied for transforming a meteorological variable into power generated, as e.g. in [50]. The main sources of uncertainty are:

If the meteorological variable (in this case the wind field) is selected from a NWP model, this will add a bias in the wind fields (determined at 10 m height or at other model levels) because the physical parameterisations of the NWP model do not perfectly simulate the dynamics of the lower atmosphere.

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[9] In this context, ensembles is referred to the output of a group of climate models and the analysis is carried out taking into account the range of uncertainties of all the climate models involve.

The wind fields obtained at 10 m height or at other model levels needs to be corrected to the hub height of the wind turbine. For this purpose it will be interpolated to the hub height of each wind turbine. This interpolation method also contributes to the uncertainty [25].

Finally, the wind speed is converted to wind power through a power curve. The selection of the power curve is also a controversial issue since each type of turbine has a different power curve. The area, geographical position of the wind farm, and the number and location of the turbines within a wind farm play also an important role in the accuracy forecasting (see for example [51]).
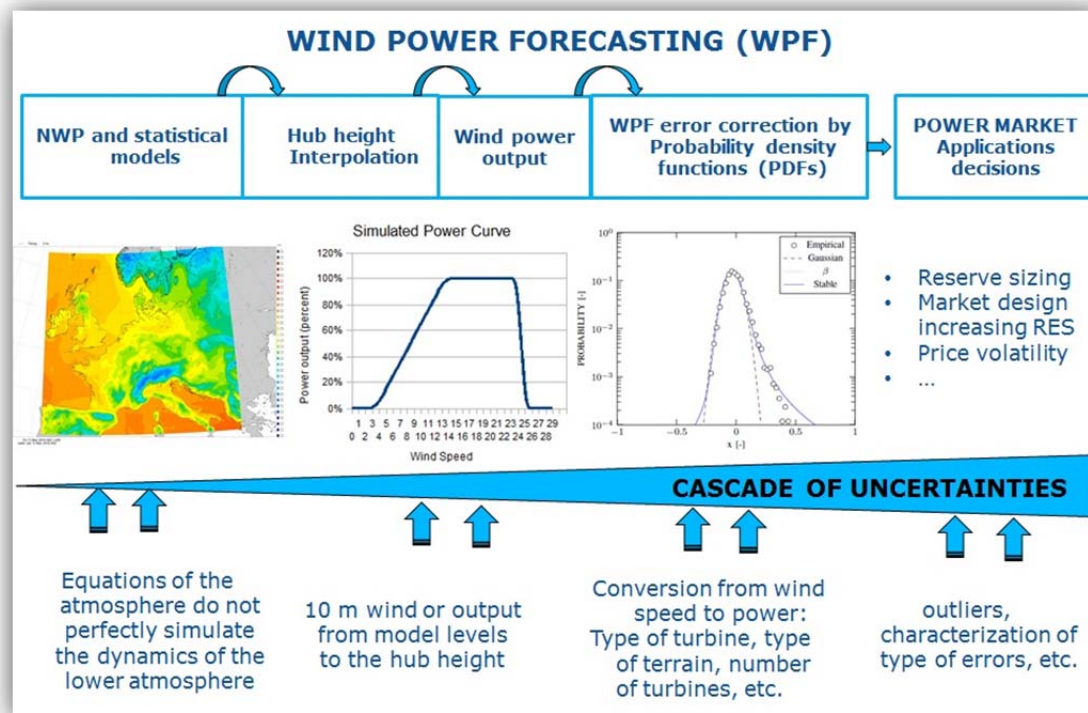
Figure 7 Sources of errors in the wind power forecast contributing to the cascade of uncertainties.

A detailed review about the methods and advances in forecasting wind power generation can be found in [52].

In *studies of the second category* the WPFE is addressed using probabilistic techniques that identify probability distribution of random variables and calculate their distribution parameters based upon historical trends.

Probability distribution functions of WPFE have been studied for different purposes: Bruninx and Delarue [53] and Bludszuweit [54] analysed the variability of the WPFE distribution for multiple power systems from different countries, fitting the hourly time series of the error to a specific distribution in order to improve the probabilistic total reserve sizing. Schertzer [55] built a prediction model to calculate the wind power uncertainty for the 24 hours of the following day and for the hour ahead for the French power system. A detailed literature review of numerical (physical), statistical and a combination of both wind power forecasting approaches can be found in [56]–[58], respectively. For example, Bri et al. [59] investigated the WPFE variability for different countries to understand the temporal variations and to help power system actors

determine appropriate corrections beforehand. The implications of integrating wind energy on day-ahead and intraday markets and the related price fluctuations have been subject to several studies in the last decade (e.g. [45]-[49]).

Rahimiyan [60] proposed a statistical cognitive model to assess the impact of wind uncertainty on market behaviour in a pool-based day-ahead market. Wang et al [61] generated wind power scenarios for a unit commitment model providing information about prediction errors by applying a Gaussian distribution to the time series. The short term relationships between wind generation and electricity prices were analysed by Vilim et al. [62], who developed a model to derive optimal day-ahead bids for wind power producers taking into account one probabilistic density function of the WPFE. The study dealing with the reduction of the time series uncertainties is done by Pinson et al. [63] who made an attempt to use short-term wind-power predictions using forecasting techniques to provide quantitatively an uncertainty estimate of the wind power output. They developed prediction risk indices (five classes) to evaluate the weather stability and the probabilities of the occurrence of high prediction errors according to the index, but the research was limited to estimating the short-term error as a function of the forecasted wind speed or other power market variables such as the total load.

Lange [64] focused on the WPFE from the forecasted wind speed and evaluated the PDF of deviations between the predicted and the measured wind speeds. In addition, since the wind power prediction is not only dependent on external wind conditions but also on the structural and mechanical performance of the wind turbines systems, Tavner et al. [65] quantified the uncertainty of overall wind energy potential prior to the construction of a wind turbine. Kwon [66] studied the uncertainty caused by the variability of natural wind and power performance in the assessment of wind energy potential at a site.

4 Review of meteorological data treatment in current RES-E integration studies

The previous sections of this report described existing tools and models used to generate the weather data used in energy system models. This section reviews a number of recently published power system studies with respect to their treatment of RES-E data time series. The studies reviewed and their main characteristics are summarised in Table 2. Information on the aim, methodological approach and RES-E data treatment can be found in the subsequent subchapters.

All of the studies reviewed used RES-E time series that originated from some weather model. Differences could be found in the approaches related to time horizon of the study, i.e. between studies focussing on the years ahead and studies looking at the longer term (2030-2050).

Studies with a short-term horizon used any of the following three approaches.

I. A NWP model is employed to obtain the meteorological data (mainly wind speed, irradiation and temperature) for a particular year at different temporal resolution. If data is required at higher temporal resolution (e.g., at 15 minutely frequency) a statistical downscaling is applied to get such resolution (e.g. the study developed by NREL).

II. Reanalysis data for a specific region (e.g. study developed by EdF).

III. Measurements in a form of time series, averaged over a region (e.g. study developed by North Sea Grid).

Studies focused on long-term analysis follow either a "typical year approach" or use climate models.

If the RES-E studies are focused on future (2020, 2030 or 2050 targets) they calculate a "type year under specific wind conditions" and then they extrapolate to the future these types of years (e.g. study developed by North Sea Grid).

Recent studies apply climate models as a tool to assess the potential future renewable energy production [48], [67]. By using a GCM for the global scale and a set of RCMs with finer resolution for Europe, the response of photovoltaic and wind energy up to the mid-XXIst century (2030 to 2050) is analysed, and different scenarios of green-house gases and anthropogenic aerosols emissions are compared (based on the latest scenarios from the IPCC). The results presented demonstrate that climate modelling is a valuable tool for investigating the future changes in PV and wind energy potentials and complementarity. Indeed, RES-E potentials show sensitivity to the simulation of different future IPCC scenarios, and a coherent relationship with the projected future modifications in the climate dynamics. This study encourages a broader use of climate models in the assessment of renewable energies future availability.

Table 2 Summary of the studies reviewed

Author and Study	Year of publication	Weather tools and data approach	Horizontal & and temporal resolution	Time frame of meteorological/ climate data used	Final purpose for RES-E integration studies
ENTSO-E SO&AF	2015	Pan European Climate Dataset (PECD): Data based on the NCAR-ARM-WRF NWP model	36 x36 km 1- Hourly	2000-2014	The Scenario Outlook and Adequacy Forecast: of the European Network of Transmission System Operators assesses the balance between supply and demand at European, regional and Member State level. System flexibility needs resulting from an increasing share of intermittent RES-E are addressed for the first time in 2015.
Pentalateral Forum System Adequacy Study	2015	Pan European Climate Dataset (PECD): Data based on the NCAR-ARM-WRF NWP model	36 x36 km 1-Hourly	2000-2014	Assessment of the generation system adequacy on regional level (AT, BE, CH, DE, FR, LU, NL). This report is comparable to the ENTSO-E SO&AF but uses an improved methodology, yet for just a subset of the EU MS (i.e. the " Pentalateral Forum").
North Sea Grid Study	2012	Time series	-	2006	Study on offshore wind power scenarios to improve current and future infrastructure development in the North Sea Area. The time horizon is 2030.
EdF - European Electricity System with 60% RES	2015	Reanalysis: ERA-Interim and ERA-40	50 x 50 km 3-hourly	31 years	Self-motivated study by the leading French power utility. Assessment of the flexibility needs of a European electricity system with a high share of RES-E.
ADEME - Vers un mix électrique 100% renouvelable en 2050	2015	Reanalysis derived from the MERRA model, provided by NASA	70 x 70 km 3-hourly	Selection of typical years of high winds in order to generate different scenarios	Study on behalf of the French government agency for energy (ADEME) on the feasibility of a 100% renewable electricity supply for France in 2050.
DENA II Grid study	2010	NWP model: EU – COSMO	6x 6 km. 1-hourly → Statistical downscaling to 15-minutely	2004-2007	Study by a large consortium of stakeholders active in the German power sector. Carried out on behalf of the German Energy Agency "dena", a public private partnership. The goal is to quantify the grid investments necessary for the integration of RES-E into the German power supply for 2015-2020.

Author and Study	Year of publication	Weather tools and data approach	Horizontal & and temporal resolution	Time frame of meteorological/ climate data used	Final purpose for RES-E integration studies
AGORA Energiewende – The European Power System in 2030	2015	NWP model: EU-COSMO	6x 6 km. 1-hourly	2011 considered as a typical year (reference) and extrapolation of the wind power at different aggregation levels for 2030.	Study on behalf of Agora Energiewende, a German think tank. The goal is to quantify flexibility needs resulting from wind and PV deployment and benefits of regional and European market integration.
NREL – Western Wind Integration Studies	2013	NWP model: WRF	2 x 2 km 10-minutely → biased and downscaling to 1-minutely by statistics	2004-2006	Three phase study sponsored by the US government Department of Energy and prepared by a team including scientists from NREL, GE, academia and consultants Investigate the feasibility of a system with 35% of RES-E (Phase 1), understand implications for the cycling of thermal power plants (Phase 2), transient stability of a high RES-E system (Phase 3).
NREL – Renewable Electricity Futures Study	2013	Reanalysis: GFS	6x6 km 1-hourly	1979- present	US government sponsored study on high RES-E penetration electricity systems (30% to 90% of energy supplied by RES-E).. The work was carried out by a group of US national laboratories, academia and consultants under the lead of the National Renewable Energy Laboratory (NREL).

4.1 European Network of Transmission System Operators Scenario Outlook and Adequacy Forecast (SO&AF) 2015

4.1.1 Aim and background

Regulation (EC) 714/2009 requires ENTSO-E to publish this report every two years along with Ten Year Network Development Plan (TYNDP). From 2015, the SO&AF will be published annually. The report [68] aims at providing stakeholders in the European electricity market with a Pan-European overview of generation adequacy with a five to ten year time frame. It assesses the balance between supply and demand at European, Regional and Member State level. In addition, system flexibility needs resulting from an increasing share of intermittent RES-E are addressed.

4.1.2 Methodology

The SO&AF does so far not explicitly model the dispatch of power plants but compared available generation capacities with maximum load at given (two most critical) moments of a year. Two scenarios (the more conservative "Scenario A" and the more optimistic "Scenario B") regarding future installed generation capacities are compared.

The challenges related to the anticipated increase of RES-E[10] in the European system have led ENTSO-E to gradually adapt the methodology applied 2015 report and in subsequent reports. It is intended to include probabilistic treatments of RES-E and other input parameters [69]. From 2017, it is intended to replace the current static approach with a market based dispatch of power plants.

4.1.3 Meteorological data treatment

The Pan-European Climate Database (PECD) has been used as the basis input for solar and wind generation and to account for the load-temperature sensitivities. A statistically relevant set of climatic time series has been generated for the analysis. The PECD dataset has been provided to ENTSO-E by the Technical University of Denmark (DTU) under a funded project [70] aimed at evaluating photovoltaic and wind hourly production on regional scale in the whole Europe.

Meteorological data; in particular, the wind speed data comes from a weather model that was developed by DTU on the basis of NCAR – ARW-WRF (Advanced Research Weather Research and Forecasting) model; initial and boundary conditions were taken from the ERA-Interim Reanalysis provided by ECMWF, V3.2.1 (2010). This approach proved to be very useful to create a coherent modelling framework where simultaneity is a key factor and the availability of measurement data is widely different across countries. Temporal resolution: 1 h; spatial resolution: 36km x 36 km; that means that the NCAR – ARW-WRF mesoscale model was used to downscale the original ERA-Interim data.

The ENTSO-E database contains aggregated data that was calculated and aggregated for each market node by the primary data provider. It does not contain wind speed data for the

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[10] The report assumes that by 2025, 22 countries are reported to have a RES capacity penetration level higher than 50%. Eight countries (DE, DK, GB, GR, IE, NI, NL and PT) will reach full hourly load penetration level (100%), not implying that 100% penetration occurs simultaneously for these eight countries on the same hour.

grid points but wind load factors only. Data was converted and aggregated to load factors by DTU using a wind power production model. This model is based on assumption on location of production (latitude/longitude) and technology mix (type of wind turbine/power curve/storm control capabilities). Similar approach is used for PV.

The ENTSO-E group does not reveal additional information about this topic.

4.2 Pentalateral Energy Forum Generation Adequacy Assessment

4.2.1 Aim and background

The study [71] mandated by the Pentalateral Forum[11] (PLEF) to the TSOs assesses the system adequacy on state and regional level up to the year 2021. This regional initiative can be seen in the context pf the Energy Union Strategy of the European Commission to deepening the cooperation at between Regions of Member States [1]. The PLEF System Adequacy Assessment, which was published in March 2015, aims at improving the methodology applied so far by the ENTSO-E SO&AF and the bottom up approach (compiling national scenarios) previously used by the PLEF. As in the case of the ENTSO-E SO&AF, understanding the impact of the expected growth of RES-E is a key motivation for conducting this study.

4.2.2 Methodology

Unlike the static approach of the ENTSO-E SO&AF, this study assesses system adequacy using two dispatch models (Antares of RTE and the in-house tool of Amprion) in parallel to validate results. Future supply and demand levels are compared for the PLEF region (AT, BE, CH, DE, FR, LU, NL) by simulating the operations of the European power system on an hourly basis over a full year. The market models combine linear and mixed integer formulations. Stochastic input variables (unscheduled outages of nuclear and fossil-fired generation units, amount of water resources, and wind and photovoltaic power production) are taken into account using a Monte Carlo approach. The study builds on the ENTSO-E SO&AF Scenario A, assessing System Adequacy for two time horizons: the winter of 2015 and 2010.

4.2.3 Meteorological data treatment

The study combines historic load data with the Pan-European Climate Database (PECD), also used by the ENTSO-E SO&AF. Correlated weather and load data is used for the production of time series (Monte Carlo scenarios) for wind and solar generation, hydro data for different climatic conditions and temperature sensitivities for system load scenarios. During this study the available PECD data were updated with weather data of the year 2012 to take into account the cold spell of the first months of this year for the simulation of extreme climate conditions. The extended PECD data (wind, solar and temperature) were used for adding sensitivity calculations for extreme cold winters.

The extreme cold front in winter 2012 is an important sensitivity which demonstrates how cold weather regional wide can have severe impact on load and subsequently the ability of the region to match demand and supply.

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[11] The Pentalateral Energy Forum was created in 2005 by Energy Ministers from Benelux countries, Austria, Germany and France (with Switzerland as a permanent observer) in order to promote collaboration on cross-border exchange of electricity.

4.3 North Sea Countries' Offshore Grid Initiative

4.3.1 Aim and background

This study [72], published in 2012 by the North Seas Countries' Offshore Grid Initiative[12], aims to evaluate benefits and disadvantages of integrated (or meshed) versus radial configurations of grids connecting offshore wind farms in the North Seas during the time period 2020-2030. Radial and meshed design topologies are compared and analysed with respect to cost/benefits, power import and export levels and the systems' CO_2 emissions.

4.3.2 Methodology

The scenarios represent national views of the 10 countries for generation and load data, based on PRIMES data for 2030. The grid situation in 2020 is defined by the 2012 TYNDP scenario and additional assumptions. Candidate grid investments are identified for the period 2020-2030.

The study combines market modelling with grid design. A market simulation is performed using the models Antares of RTE (also used in the study by the Pentalateral Forum), PowerSYM and PROMOD IV. Market models are combined with power flow models to identify the most cost effective among a multitude of previously identified potential grid investments.

4.3.3 Meteorological data treatment

The publications mentions that "Capacity factors and wind speeds for these wind generators were derived from correlated European wind power time series from 2006, scaled as appropriate to match defined 2030 capacities". Data for solar PV and other RES-E were taken from "a set of correlated profiles", without additional information about the methodology for weather data treatment. The reference found in this study is the SafeWind project [73]: Multi-scale data assimilation, advanced wind modelling and forecasting with emphasis to extreme weather situations for safe large-scale wind power integration. They used different tools (ensemble NWP models and statistical techniques such as the Neural Networks) and correction of the WPF uncertainties in order to improve wind predictability and the impact of extremes at different spatial scales (local, regional and European). This project is led by the ANEMOS consortium [74], which aims at the optimal management of electricity grids with large-scale wind power generation. For this purpose, the project develops new intelligent management tools for addressing the variability of wind power. Emphasis is given on the integration of wind power forecasts and related uncertainty in power system key management functions.

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[12] The North Seas Countries' Offshore Grid Initiative is a regional cooperation of 10 countries to facilitate the coordinated development of a possible offshore electricity grid in the greater North Sea area. This cooperation, formalized by a Memorandum of Understanding in 2010, following a Political Declaration in 2009, is supported by the energy ministries, the regulators and transmission system operators of the 10 participating countries, and the European Commission.

4.4 Technical and Economic Analysis of the European Electricity System with 60% RES by Electricité de France (EdF)

4.4.1 Aim and background

This study [75] was published in June 2015. It examines the integration of a large share of RES-E into the European power system.

4.4.2 Methodology

The scenario studied is derived from the high RES scenario of the EU 2050 Roadmap 2011 [76] which implies a 60% share of RES-E in 2030 electricity generation mix of the European Union.

The study uses the EdF power system optimisation tool CONTINENTAL in combination with a capacity expansion module, a probabilistic tool for near-term flexibility analysis and a dynamic simulation platform for frequency stability analysis. CONTINENTAL is a power system model with water management, and stochastic hydro-thermal generation scheduling based on chronological data with hourly (or lower) resolution. FLEX ASSESSMENT/OPIUM: a probabilistic tool used to estimate flexibility adequacy considering the operation margin requirements to handle short term load-generation balancing uncertainty. FLEX ASSESSMENT is used to further improve the results of CONTINENTAL by assessing the flexibility adequacy of the generation mix.

4.4.3 Meteorological data treatment

The analysis provides a rigorous representation of spatial and temporal effects relevant to power system planning and operation. In order to analyse the impact of wind and PV on the electricity system, the study represented the stochastic nature of the wind and PV generation, depending on atmospheric conditions and the accuracy forecasting of such phenomenon.

A dataset of 30 years of weather observations is used for generating hourly time series for onshore wind, offshore wind and PV for every country. The meteorological data used in the CONTINENTAL model are provided by the ECMWF reanalysis. It uses wind, radiation and temperature simulated by the ERA Interim (1979-2014) and ERA 40 model (1958-2002) assimilation system. The spatial resolution is the native one (approximately 80 km for ERA interim and 120 km for ERA 40). For each day there are four data (measured at 00h, 06h, 12h and 18h) and the forecasts (H+3) produced from analysis at 00h and 12h.

4.5 Vers un mix électrique 100% renouvelable en 2050 by the French Environment and Energy Management Agency (Ademe)

4.5.1 Aim and background

This ongoing study [77] is financed by ADEME, the French National Energy Agency. It is carried out by a consortium of consultants and research institutions (Artelys, ARMINES-Persee, Energies Demain). A first report was published in the summer of 2015. The study addresses under what constraints it is possible to provide electricity at 100% renewable energy; what are the optimal energy mix, associated with various projections technological developments, consumption, etc.; how are geographically distributed different means of renewable production and what are the economic impacts of a 100% renewable mix.

4.5.2 Methodology

The study uses an hourly dispatch model. Power flow is modelled between the different French (Mainland) regions which are themselves modelled as copperplates. The model optimises operation and investments in generation and grid. There are 15 distinct renewable energy generation technologies.

The optimised generation portfolio is tested on six weather scenarios available (in all, more than 60,000 hours of different combinations of consumption, solar irradiation and wind). The optimised mix satisfies the supply-demand balance on all six of the seven hours of weather scenarios studied. An additional seventh scenario with a period of two days represents a situation with an extremely high demand and almost no wind power. The study concludes that 11 GW of lost load or extra storage would be needed in that case.

4.5.3 Meteorological data treatment

The study assesses the potential for different RES-E in each region according to the natural resources available. In a first step the possible production is derived from reanalysis data for wind speed and solar radiation data on the ground originating from the MERRA model. Power generation time series are obtained from conversion models which are statistically calibrated [78]. To ensure the validity of the PV production time series, the parameters on which they rest were estimated using actual production data (provided by RTE and Solais).

The generation of potential maps covering all the territory have allowed a first analysis of the regions with high potential renewable production. In a second step, exclusion zone constraints are integrated, covering both technical (e.g. type of floor space and adequate relief), legal (e.g. preservation of protected natural reserves, distance minimum to homes, etc.), and economic aspects.

The study also includes a methodology to quantify the reserve needs to forecast errors of wind and photovoltaic production (from the Smart Reserve project).

4.6 DENA II study

4.6.1 Aim and background

The dena II grid study [79] was published in 2010 as a follow up of the dena I study. The aim was to determine the grid investments necessary during the time period between 2015 and 2020 (under the assumptions regarding the expansion of RES-E prevailing at the time[13]). The consortium involved in the study includes TSOs, DSOs, traditional utilities, operators or RES-E, manufacturers and consultants. The study was published on behalf of the German Energy Agency (dena), a public-private partnership.

4.6.2 Methodology

The dispatch and capacity planning for the power generation portfolio ae optimised using the models DIANA and DIME, developed by EWI Cologne, respectively. Power flows are modelled using a PTDF matrix between different German regions of copper plates. A detailed optimum power flow model has been used to generate the PTDF matrix.

4.6.3 Meteorological data treatment

Time series are generated for the feed-in of electricity from wind power and other renewable energies for the year 2020. The methodology for the simulation of wind power time series for 2020 is largely based on the conversion of historical data from a NWP model: the EU-COSMO model of the German Weather Service (DWD), to the wind power output for 2020. Time series are generated for onshore and offshore wind power using the EU-COSMO for years 2004 to 2007. The study argues that these four wind years are suitable for the intended analysis because they comprise two weak, one average and one strong wind year.

The spatial resolution configured for the performance of the NWP is 0.0625° by 0.0625° and the temporal resolution is one hour. For each of the 1232 grid nodes and wind farm locations, the air pressure and temperature at 2 m above ground, wind directions and wind speeds at three elevations above ground (e.g. approximately 34 m, 69 m und 116 m) are extracted from the NWP model. Based on the three height levels (layer centres), the wind speeds are interpolated to the hub heights of wind turbines or to the average capacity-weighted hub height. Air pressure and temperature are used for the density adjustment of power outputs. The weather model data is complemented with data from wind measurement masts in order to achieve a higher temporal resolution of 15 minutes with which the wind power time series for 2020 were generated.

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[13] RES-E expansion assumed in dena II differs from the actual deployment path observed following the study, e.g. the PV capacity installed at the end of 2014 exceeds the assumed capacity in 2020 while offshore wind deployment is lagging behind the dena II assumptions.

4.7 Agora Energiewende study on The European Power System in 2030 Flexibility Challenges and Integration Benefits

4.7.1 Aim and background

Agora Energiewende commissioned a study by Fraunhofer-Institute for Wind Energy and Energy System Technology (IWES), publicly made available in June 2015 [80]. The study entitled "The European Power System in 2030: flexibility challenges and integration benefits" conducts an in-depth, model based analysis of future scenarios in the European power system over the Pentalateral Energy Forum (PLEF) Region – Austria, Belgium, France, Germany, Luxemburg, the Netherlands and Switzerland. It aims at understanding the flexibility needs resulting from the deployment of wind power and PV as well as the benefits of regional and European market integration to avoid investments into flexibility assets. The authors assess the effects of the spatial decorrelation between single RES-E generators and the resulting geographical smoothing effects, in particular the reduction of extremely high and low values.

4.7.2 Methodology

The European power system of the year 2030 is optimised using a unit commitment model developed at Fraunhofer IWES. The model covers 25 mostly EU countries. Each MS forms a copper plate. Power flow between regions is NTC based.

4.7.3 Meteorological data treatment

Time series for RES-E are generated by applying a NWP model, the COSMO-EU model of the German Meteorological Service, for the year 2011. This year is considered as a typical year and used for extrapolating the wind power at different spatial aggregation levels in 2030. Also, spatial temperature profiles of 2011 are used for determining the smoothing effects of electricity demand.

4.8 Western Wind Integration Studies by the National Renewable Energy Laboratory (NREL)

4.8.1 Aim and background

This three phase study on the integration of wind and solar energy into the North American Western Interconnection[14] was published between 2010 and 2014 [62], [63], [64]. It was sponsored by the US government Department of Energy and prepared by a team including scientists from NREL, GE, academia and consultants. Phase 1 focuses on the technical feasibility of high RES-E penetrations. The study assesses the operation of the West-Connect[15] group of utilities with a up to 30% energy generated by wind and 5% generated by photovoltaic (PVs), and concentrating solar power. Phase 2 takes a closer look at increased cycling of thermal power plants due to an increasing share of RES-E. Phase 3 assessed the frequency response and the transient stability of the respective power system. A similar exercise was also carried out for the Eastern Interconnection [84].

4.8.2 Methodology

In Phase 1 an hourly power plant dispatch model (MAPS of GE) was combined with statistical data analysis, sub-hourly simulations and a system adequacy analysis. Power flow is modelled between 106 regions, for which individual load profiles as well as RES-E production time series are prepared. A minute to minute dispatch is carried out to determine the load-following requirements of the power system under conditions of large wind and solar variability. Phase 1 concludes that a system generating 35% of RES-E can be realized with the existing conventional power plant portfolio.

In Phase 2, the impact of cycling was determined using the commercial power system simulation tool PLEXOS. The model simulates the operation of the entire Western Interconnection but wind and solar generation only added to the U.S. part of the Western Interconnection.

4.8.3 Meteorological data treatment

Lacking sufficient measured data the wind resource across the entire western United States was modelled in order to generate a consistent wind dataset in space and time. The Weather Research and Forecasting (WRF) mesoscale NWP model was applied over the region at a 2 x 2 km, 10-minute horizontal and temporal resolution, respectively, for the years 2004-2006. Due to the high computational resources required for this purpose, it was necessary to divide the region into four geographical domains that were run independently and merged thereafter.

In Phase 1, the WRF NWP model was used to synthesise wind speeds on a 10-minute, 2-km interval in the U.S. portion of the Western Interconnection. A total of 960 GW of hypothetical wind plant output for 2004 to 2006 was generated.

Although the wind output for each site respected realistic 10-minute maximum changes in output, unrealistic 10-minute variability occur when sites are aggregated. In those simulations, the model output contains temporal seams that were not possible to resolve.

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[14] The North American (Us and Canadian) power system is comprised of four synchronised areas: The Eastern Interconnection, the Western Interconnection, the Québec Interconnection and the Texas Interconnection. DC connections exist between these synchronous areas.

[15] This spreads over the states of Arizona, Colorado, Nevada, New Mexico, and Wyoming.

This results in unrealistic wind energy ramps near the temporal boundaries, which occur every 3 days. A continuous annual record is needed to obtain a complete reserves and ramping analysis, so a method to smooth those ramps below statistical significance was required. Phase 2 evaluates various approaches to yield realistic variability when sites are aggregated, along with realistic spatial correlation between sites.

The method that worked best includes random splicing of data from unaffected days to the affected seams. This approach is used to correct the wind data for Phase 2. Additionally, a number of approaches to mitigate the higher variability at the seam are evaluated. These include filtering the supplied data, synthesizing new data based on the average sigma of the 10-minute changes, and randomly splicing data from "good" days to the affected ranges. The performance of the method seems quite good.

Downscaling from 10 to 1 minutely frequency

The interpolation between each 10-minute interval and the simulation of power variability from a set of real wind turbines with a total capacity of 30 MW are calculated using statistical down-sampling based on measured 1-minute output from wind plants in the Western Interconnection. The high-frequency range of actual data is used to simulate the high-frequency variability between the 10-minute intervals of wind power data provided by one project partner (3TIER).

A fast Fourier transform, which has previously been used for power spectrums of wind data, is applied to measured wind plant output from the Cedar Creek Wind Farm in Colorado. First, a cubic spline interpolation is applied to the 10-minute data to obtain power estimates at 1-minute intervals. Then high-frequency data from the measured Cedar Creek wind plant is used to generate the noise component of the wind power data.

4.9 Renewable Electricity Futures Study by the National Renewable Energy Laboratory (NREL)

4.9.1 Aim and background

This US government funded project studies the possibility of supplying a large share of electricity in the US by renewable energy sources [85]. The RES-E penetration levels in the different scenarios assessed vary between 30% and 90% of energy supplied thus above the levels studied in the Western and Eastern Renewable Energy Integration studies. The work was carried out by a group of US national laboratories, academia and consultants under the lead of the National Renewable Energy Laboratory (NREL).

4.9.2 Methodology

The study combines the ReEDS generation and transmission capacity expansion model of the US electricity system with the GridView integrated unit commitment and DC power flow model developed by the company ABB. ReEDS is a linear optimisation model based on 17 time slices and 134 balancing areas plus 356 wind and solar resource regions. Generation adequacy and reserve contingencies treated based on statistical considerations. The analysis with the ReEDS model was complemented by an hourly simulation using GridView in order to address forecast uncertainties, ramping constraints and curtailment. The analysis concluded that a RES-E penetration level of 80% was in principle feasible.

4.9.3 Meteorological data treatment

The study uses a dataset of regional wind resource and wind plant output that was published by NREL in 2010 [85]. The preparation of this dataset included the generation of wind power time series, the validation of wind power generation and forecasted data. The forecast data modelling was using the Global Forecast System (GFS) information. In order to obtain actual information used to perform state-of-the-art forecasting the models were run with a 6 x 6 km^2 resolution and the model output was stored at the hourly timescale, which enabled to run the wind forecast model as a single large domain.

The data is accessible for the US domain provided by the NCAR/NCEP Reanalysis dataset.

5 Summary and conclusions

5.1 Comparison of approaches found

This report compares the methodologies for weather data generation used in recent renewable energy integration studies. The generation of RES-E generation data is clearly an active field of research. Different approaches to obtain weather data with specific characteristics could be identified.

Methodologically there seems to be a clear trend to use time series generated by reanalysis or by their own meteorological model performance. The geographical resolution of these data was between 70x70 km and 2x2 km [81]. The time resolution is at least hourly, with some studies using sub-hourly data for the purpose of studying effects of forecast errors. On site measurements were used in some cases to validate weather forecast model output when generating time series for very short time intervals.

No clear trend could be observed for the selection of the "meteorological years" that were used or the power system assessments. Some studies [77] and [80] make use of typical years while others use longer time datasets. Results obtained from data sets with a reduced number of years may require additional analysis for ensuring robustness.

In general, using RES-E data bears a risk of using imperfect, inappropriate or incomplete data which might lead to errors in the assessment of solar/wind resources. Consequently, analysis based on current studies always bears the risk of either overstating or downplaying the possible role of solar and wind energy in the future energy mix.

5.2 Conclusions for analysis on the European power system

Any RES-E data set used for assessing the adequacy of the European power system will need to meet a number of requirements.

    The geographical coverage should be Europe (EU Member states and neighbouring countries).
    The data set provides a consistent picture of wind speeds and solar irradiation[16]
    The time resolution is at least hourly for the primary data set.
    Additional information is available for generating possible production profiles for shorter (than hourly) time steps.

To the best of the author's knowledge, there currently exists no publicly available database meeting these requirements. Wind and PV generation data would thus need to be calculated following a procedure as suggested in **Figure 8**.

In order to obtain high quality wind data, the following requirements should be met for the generation of wind power time series. In the case of solar power, similar methodology could be applied. Note that since the radiation variability is lower than the variability of the wind speed, the horizontal resolution could be coarser. Also, the solar power output is nearly linear with irradiance.

- Wind speed data should ideally be obtained from a meso meteorological model at high horizontal resolution or by a micro scale meteorological model.

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[16] Temperature (relevant for the modelling of demand) and precipitations or reservoir inflows (for modelling of hydropower) would also be needed for a comprehensive power system analysis.

- The time resolution of the weather data should be at least hourly, preferably a shorter time interval (as done by NREL for the Western Wind and Solar Integration Study) if computational resources are available.
- The spatial resolution should ideally be less than 5 x 5 km in order to capture the small scale variability due to the topographical variation present across Europe.
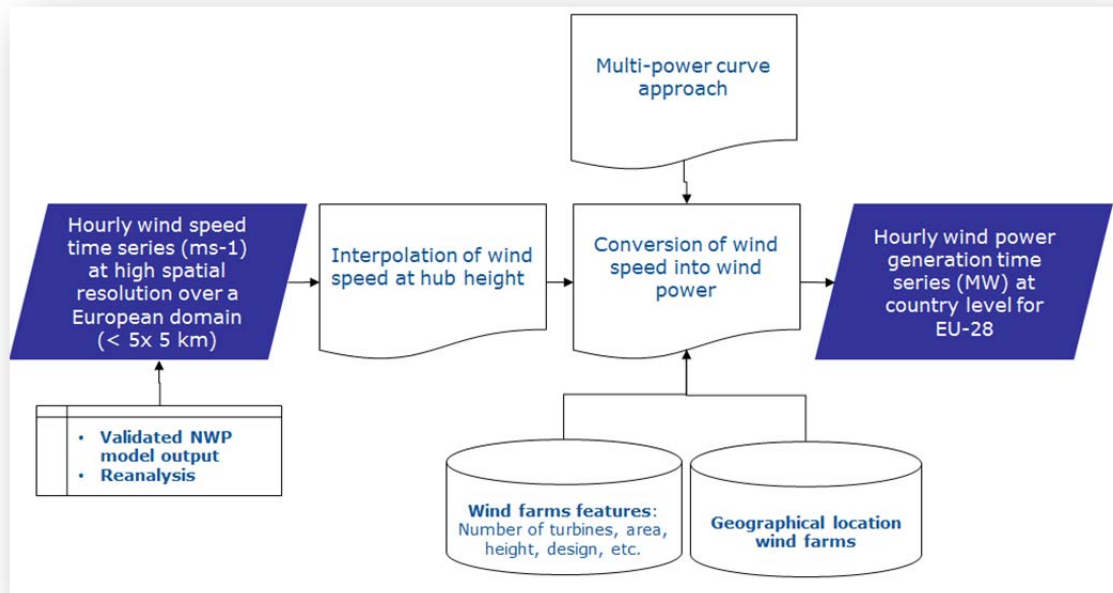
Figure 8: Flow chart for the methodology to obtain the wind power generation hourly time series over the EU-28 derived from weather data

In addition to the wind speed data, care needs to be taken with respect to technical data of wind turbines.

- The height of the wind turbines needs to be taken into account by interpolating the wind speed to the hub height. The methodology for this will depend on the original wind speed dataset.
- For the conversion of the meteorological variable into power, it is important to take the respective power curves into account. For the actual situation, the best estimation would be done based on a multi-power turbine approach, selecting the specific power curves according to the manufacturer and overlapping the wind speed with the geographical location of the wind farms over Europe. For future scenarios (with yet unknown wind turbines) an estimation of the power curve for broader types of turbines would be also required.

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