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Development of a global electricity supply model and investigation of electricity supply by renewable energies with a focus on energy storage requirements for Europe

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Abstract

Electricity supply at present requires about 38 % of the global primary energy demand and it is likely to rise further in the coming decades. Facing major problems, such as limited resources of fuels and an ongoing anthropogenic climate change, a sustainable electricity supply based on renewable energies is absolutely vital. Wind and solar power will play an extensive role in future supplies but require energy storage capacities to meet electricity demand.

To investigate the relationship of power plant mix and required energy storage capacity, a computer model based on global weather data has been developed to enable the simulation of electricity supply scenarios by up to ten different power plant types for various regions.

The focus of the investigation has been on the energy storage requirements of an electricity supply for Europe by wind and solar power. The minimum required energy storage capacity for a totally weather dependent electricity supply occurs at a ratio of 30 % wind and 70 % photovoltaic (PV) power plant capacity installed. Thus, the required energy storage capacity rises from a transition of to-day's electricity supply to the afore-mentioned 100 % renewable wind and PV scenario exponentially to about 150 TWh (3.8 % of the annual electricity demand).

The installation of additional excess wind and PV power plant capacity was seen to be an efficient way to reduce the required energy storage. Already 10 % excess capacity lead to a reduction by 50 % of the required storage capacity.

To use different storage technologies in an optimised way in terms of storage capacity and efficiency, the storage tasks can be separated into a daily and a seasonal usage. While the seasonal storage capacity has to be about two orders of magnitude larger than the required capacity of the storage for the daily cycle, the sum of stored energy during one year is almost equal for the long and short time storage.

In summary, an electricity supply by wind and PV power was shown to be completely feasible regarding the required energy storage capacity together with the required land area for power plants, and with electricity generating costs of 0.09 EUR to 0.18 EUR per kWh depending on the power plant mix, excess capacity, and storage investment costs.

Zusammenfassung

Die Elektrizitätsversorgung hat einen Anteil von ca. 38 % am weltweiten Primärenergie-bedarf und sie wird in den nächsten Jahrzehnten weiter wachsen. In Anbetracht von Problemen wie die Verknappung limitierter Brennstoffe und dem anthropogenen Klimawandel, ist eine nachhaltige Elektrizitätsversorgung durch die Nutzung erneuerbarer Energien nötigt. Wind- und Solarenergie werden als Hauptquellen für die zukünftige Elektrizitätsversorgung angesehen, jedoch werden Energiespeicher benötigt um die Elektrizitätsnachfrage decken zu können.

Um die Abhängigkeiten vom Kraftwerkmix und Energiespeicherbedarf untersuchen zu können, wurde ein auf globalen Wetterdaten basierendes Computermodell entwickelt, das Simulationen von Elektrizitätsversorgungsszenarien mit bis zu zehn verschiedenen Kraftwerksarten für beliebige Regionen ermöglicht.

Der Fokus der Untersuchungen lag hierbei auf den Anforderungen an Energiespeicher für eine Elektrizitätsversorgung Europas durch Wind- und Solarenergie. Bei einem Mix aus 30 % Wind- und 70 % Photovoltaik- (PV) installierter Kraftwerkleistung fällt die geringste benötigte Energiespeicherkapazität für eine gänzlich vom Wetter abhängige Elektrizitätsversorgung an. Der Umstieg vom heutigen Elektrizitätsversorgungssystem auf das genannten 100 % regenerative Wind und PV Szenario führt zu einem exponentiellen Anstieg der Energiespeicherkapazität auf rund 150 TWh (3,8 % des jährlichen Elektrizitätsbedarfes).

Das Installieren von Überkapazitäten an Wind- und PV- Kraftwerken zeigte sich als effektive Methode um den Energiespeicherbedarf zu reduzieren. Bereits 10 % Überkapazität halbieren den Speicherbedarf.

Um unterschiedliche Speichertechniken bezüglich ihrer Speicherkapazität und ihrem Wirkungsgrad effizient zu nutzen, können die Speicheraufgaben auf tägliche und saisonale Zeitskalen aufgeteilt werden. Hierbei ist die benötigte saisonale Speicherkapazität fast zwei Größenordnungen größer als die des Speichers für den Tagesverlauf bei gleichem Jahresenergieumsatz für den Lang- und Kurzzeitspeicher.

Letzten Endes kann man festhalten, dass die benötigten Energiespeicherkapazitäten, die Landfläche für die Kraftwerke und auch die Elektrizitätsgestehungskosten von 0,09 EUR bis 0,18 EUR pro kWh je nach Kraftwerkmix, Überkapazität und Speicherkosten für eine Versorgung Europas durch Wind- und PV- Energie realisierbar sind.

Contents

1. Introduction

’*The best way to predict the future is to invent it.*’ Alan Kay (1971)

The global demand for primary energy was about $5.3{\cdot}10^{20}$ J in 2010 (van der Hoeven, 2012). This energy demand is approximately 8 % of the amount of total biomass growing during one year on the globe (Kleidon, 2012) and thereby a significant share of the earths energy budget. 81 % of the primary energy comes from fossil fuels such as coal, oil and gas. Fossil fuel combustion leads to CO_2 emissions of 30.2 Gt forcing the anthropogenic climate change.

The electricity sector is responsible for about 38 % of the global primary energy demand and it is likely to rise further in the coming centuries (van der Hoeven, 2012). Fossil and nuclear fuels are the dominant energy source of today’s energy system, but there are important reasons to substitute them by renewable energies. Any used finite resource will ’peak’ some day in its maximum extraction rate. When reaching this point for the fuels the present electricity supply system is based on, the price will rise for this resources and it will be hard to supply the electricity demand. Regarding oil, ’peak oil’ is expected to happen in the first decade of the 21st century or might have even occurred in 2005 / 2006 (Bardi, 2009). Thus, it is of most importance to adjust the energy system as soon as possible.

Beside the limitation of the fossil energy sources, the effects on the environment due to the extensive use of fossil and nuclear fuels are important as well. Especially coal fired power plants lead to heavy smog events, for example in China (Wang and Kwok, 2003), and influence the quality of live and health (Villiger, 2007). Also, the question of how to store radioactive waste coming from the nuclear power plants is still an open topic and the search for depositories goes on while the nuclear wast is still increasing.

Finally, anthropogenic climate change due to CO_2 emissions with its related damages is one of the major challenges of our time. Global warming will increase the chance of strong rain and flooding events, dry periods and heavy storms. The Intergovernmental Panel on Climate Change (IPCC) recommends to keep the global warming due to anthropogenic green house gas emissions below 2°C to reduce the risks related to the anthropogenic climate change. Environmental effects such as sea level rise that will threaten residential coast areas and extreme weather events with related problems such as hunger due to crop failure and shortage of drinking water underline the importance to act (IPCC, 2007). The Stern review on the economics of climate change mentions that the cost to stabilise climate change are high, but a delay will most likely lead to dangerous changes and adapting to the changes will cost much more (Stern et al., 2006).

In order to reduce global anthropogenic green house gas emissions, the Kyoto protocol of 1997 was established where the industrialised nations agreed to reduce the green house gas emissions by a minimum of 5 % of the 1990 emissions. At the Conference of the Parties (COP18) in Doha 2012 the Kyoto protocol was extended until till 2020. In order to fulfill the climate goals, the energy supply is needed to be based on renewable energies instead of fossil fuels. The electricity generation sector is the major anthropogenic CO_2 source with approximately 26 % of the total emissions (Wheeler and Ummel, 2008). Therefore a transition of the electricity generation sector is an important task for our and future generations. For example, in 2013 about 23 % of the electricity generated in Germany was based on renewable energies but to reach climate goals such as a 80 % to 95 % reduction of green house gas emissions till 2050 (Klaus et al., 2010), much more effort has to be done and options need to be evaluate.

The earth system offers a variety of renewable energy sources such as solar radiation, wind, waves and tides, bio fuels or geothermal. Solar radiation is the driving force for the renewable energies, except for tide and geothermal energy. About $2.426 \cdot 10^{24}$ J of solar energy reach the earth surface each year (Mayer, 2010). In comparison the annual anthropogenic energy demand is only about 0.02 % of this figure. Due to the geographical differences in solar iradiation, temperature gradients establische that drive the atmospheric circulation and the thermohaline circulation of the ocean. An estimation for the atmospheric circulation by Kleidon (2012) lead to a theoretical annual energy of about $3.154 \cdot 10^{22}$ J from wind. Even if just a small fraction of the renewable energies could be used for the energy supply, their potentials are still sufficient, but, as the energy density is low compared to fossil fuels, much more land area will be required for a supply system based on renewable energy sources.

A major difference in the characteristics of a renewable electricity supply such as solar and wind power compared to the today's electricity supply, is the volatile availability. Additional controllable power plant capacities such as bio-fuel, hydro electric power or especially energy storage capacities will need to play an essential role of the future electricity supply system to balance electricity generation and demand. To investigate the requirements and work out future strategies, the modelling of energy supply systems is required.

1.1. Modeling of electricity supply

Today a wide range of energy supply models already exists. Usually heir objectives are to investigate energy supply strategies by a cost optimising approach. Two major categories can be separated among the energy models:

1. Economic models: Long term economic and politic strategy models that simulate the development of the electricity supply system for a period of decades up to centuries.

2. Physical models: Electricity supply optimising models, with a focus on a detailed simulation of electricity supply usually over a period of one year.

The physical supply models are typically base on weather data of solar radiation, wind speed and many more to explicitly calculate electricity generation by renewable energies, typically on a one hour time resolution. This is done by different models on a model grid for varying regions from national to global size. Since the major variations in electricity supply occur during the course of one year, this time period often represents the typical time horizon for the simulations of this models. Longer time periods require enormous volumes of data and are, therefore, rarely simulated.

Economic models, typically simulate energy markets with a reduced spacial and temporal resolution, but for a longer time period.

1.2. Motivation

Considering the challenges mentioned in the section above, the goal of this thesis is to present an overview over the general behaviour of electricity supply systems mainly based on wind and solar power as this are supposed to be the most processing energy sources of future electricity supply (Heide et al., 2010).

In order to investigate the behaviour of the combination of different power plant types under the influence of hourly varying electricity supply and energy storage requirements, the Meteorological based Energy Equilibrium Testing (MEET) model has been developed as part of this thesis. With this tool, all kind of electricity supply scenarios can be considered with up to ten different power plant types from fossil fuel burning to full renewable. It can be set-up easily to analyse the requirements for different regions and weather conditions of eleven years.

Because the transformation of the electricity sector is a process which requires planing and installation times in the order of a decade, it is important to understand the options and requirements for a sustainable future electricity supply.

1.3. Outline

This thesis was written at the Institute of Environmental Physics of the University of Heidelberg as part of a research project by the Heidelberg Center for the Environment (HCE) on global energy supply.

First an overview of energy models is given in section 2 to show the state of the art and theory of modeling electricity supply. This is followed in section 3 by a detailed description of the MEET model which has been developed as part of this thesis to investigate electricity supply scenarios. To evaluate the representation of electricity supply in the MEET model, in section 4 the model output was compared to other electricity supply scenarios and existing power plants as well. In section 5 the investigated supply scenarios and the model results are presented. A discussion of the results and resulting requirements of electricity supply options based on renewable energies can be found in section 6 followed by a summary and conclusion in section 7.

2. Overview of existing energy supply models

To investigate complex fields like energy supply strategies, computer models turned out to be a good tool. Actually the reality of energy supply is too complex to be represented by a single model. So a model must be reduced to the main points that have to be investigated, but still in this way on can learn a lot of the behaviour of the modelled systems. In this section an overview of different models of the energy sector is presented, followed by a detailed description of the Meteorological based Energy Equilibrium Testing (MEET) model in section 3 which has been developed for this thesis.

There exist a variety of different models for research on energy issues on all scales. Usually these focus on economic questions, investigating potentials and needs of energy supply or are specialised for detailed technical questions. Often energy potentials and economical aspects are combined, because in fact they belong to each other in our society. But on in the case of this combined models, the model results will be influenced by even more assumptions than specialised models. So, for example, to estimate learning curves of technology prices for the next 40 years is quite challenging, but it will have an essential influence on the power plant types that such a model will prefer for its development of a future energy mix (Junginger et al., 2008).

The variety of energy models cover almost all areas of investigation from a very local or National up to a global view. So, the model for simulation of the feed in of renewable energy (SimEE)[1] developed by the Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES) represents the National scale. An example for a continental scale model would be the Renewable Energy Mix for sustainable electricity supply (REMix) of the Deutsches Zentrum für Luft- und Raumfahrt (DLR). For the global scale models as the world energy model (WEM) of the International Energy Agency (IEA), the Dynamic Integrated Climate-Economy (DICE) and the Regional Integrated Climate-Economy (RICE) model from Yale University or the model for Global Resource Extraction and Energy Transformation (GREET) developed by Zentrum für Europäische Wirtschaftsforschung (ZEW) can be mentioned. It should be said that, indeed, there are many more models than those mentioned in this thesis, but these models are quite enough to provide an major overview of modeling activities of the energy sector.

The way energy models are designed and programed has a wide range from a smart Excel solution over common programming languages up to a complex use of GIS-databases (Geographical Information System) and optimizing programing like GAMS (General Algebraic Modeling System) or the R language for statistical computing solutions.

[1] Simulation der einspeisung Erneuerbarer Energien

Whilst talking of energy models, in most cases those models focus on the electricity sector. Some also relate to the an other large energy sectors, the heat distribution sector or the transportation sector, or even couple these different sectors in one model. This theses focus on the electricity sector, since it is, with approximately 26 % of global anthropogenic CO_2 emissiones, the sector with the highest CO_2 emissions (Wheeler and Ummel, 2008). As the need for electricity will continuing to rise in the future (van der Hoeven, 2012) and by comparison to heat and transportation, electricity is not substitutable as using better insulation for buildings to reduce the demand of heat or reducing the need for fuels due to the use of electric cars, the electricity supply sector is of major interest.

2.1. The GREET model

The model for Global Resource Extraction and Energy Transformation (GREET) is a computable partial equilibrium energy model (Grogro, 2012) developed at the Zentrum für Europäische Wirtschaftsforschung (ZEW) Mannheim. The model is based on the General Algebraic Modeling System (GAMS) (Rosenthal, 2014). It focuses on the economical view of extraction, trade, transformation and consumption of energy carriers while optimizing the different markets. A detailed description of the GREET model can be found in Grogro (2012), which is also the main reference for this section.

GREET considers the whole global effect while subdividing it into eleven model regions: North America, South America, Europe, the Former Soviet Union, the Middle East, Africa, Australia, China, India, Japan and Other Asian Pacific countries. For a detailed list see the appendix of Grogro (2012). Since the GREET model considers the regions only with their characteristics of energy demand, resources or distance to other regions, it does not need a geographical grid for its calculations. As a time horizon a typical range of about 50 years is used with a time step of five years for the calculations.

On the first level, the GREET model requires a lot of different data that need to be defined such as the discount rate for investments set to 3 % (Grogro, 2012) or exogenous learning path for the investment in available technologies. Data for boundary and initial conditions are needed like resources of primary energy carriers or extraction capacities. The initial year 2007 was choosen and is defined by using data of the Organisation for Economic Co-operation and Development (OECD) energy balances (IEA, 2008), BP Statistical Review of World Energy 2007 (BP, 2008) and further sources mentioned by Grogro (2012).

For all model regions, extraction of primary energy carriers is done within the boundary conditions of exogenous given resource limitations and endogenous decisions on the available capacities for extraction at base level. The primary energy carriers of GREET are uranium, coal, natural gas and crude oil. In addition the GREET model considers renewable energy carrier conversion technologies to supply a region with electricity. Therefore, wind, water, biomass, solar photovoltaics (PV), tide-wave-ocean and geothermal energy can be used (Grogro, 2012). Biomass is used as well for providing fuel. For the heat sector, geothermal, solar-thermal and biomass technologies offer additional options. The investment into renewable technologies is limited by the potentials of the model regions to build the renewable energies converters derived from the IPCC Special report on renewable energy sources (2011).

On the second level of the model regions the trading of primary energy carriers are organized. Here, a region can use its own energy carriers or trade with other regions while considering trading capacities and costs of transportation. This is the point where global interaction takes place.

The third level is given by the transformation sector that converts the primary energy carriers into final energy goods to supply the individual regions. These final energy goods are subdivided into electricity, liquid fuels, heat and direct demands of natural gas and coal.

The fourth and last level of the model regions is given by the overall demand of the final energy needs. Since GREET does not model other sectors of economic activities the demand for final energy of the model regions is set up as an exogenous demand path.

Therefore, the economic actions in the GREET model are divided into three main markets with many participants trying to maximize their profits for the optimization in GREET. The first market is at the point of extraction to maximize the profits from the extraction of finite resources within a particular region for all time steps, while future profits are considered by a discount factor. The second market is defined by the trading with primary energy carriers and the trade with other model regions. Therefore those involved can invest in transportation capacities and the setting up of trade agreements, each associated with specific costs. At the third market, the primary energy carriers get transformed into the required final energy. To maximize the profits of this market, the costs of the primary energy carriers from the traders and the cost of transportation, the transformation itself and the transformation capacity investments have to be considered by the GREET model. At this market renewable energy participants and want to maximize their profits, as a trade-off between the revenues of selling final energy and the cost of generating and investing in the generating capacities. For those renewable energies which are volatile, an additional electricity storage constraints are introduced to consider these costs as well.

2.2. The REMix model

REMix (Renewable Energy Mix for sustainable electricity supply) is a linear optimization model developed by the Abteilung für Systemanalyse und Technikbewertung Stuttgart of the DLR (Deutsches Zentrum für Luft- und Raumfahrt) to simulate the supply of energy in a system with a high share of renewable energy sources. It covers the region of Europe and the north of Africa. More facts about REMix can be found in Scholz (2010), Nitsch et al. (2010a) and Scholz (2012), which are also the main references for this section.

The simulations are done for a time horizon of one year under the proposition of a cost optimization of the energy mix by making use of GAMS (Rosenthal, 2014). Therefore, cost-potential-curves are used in combination with a GIS data base including meteorological data for the simulation of renewable energy supply. To get an idea of the influence in the fluctuation of the weather during different years, weather data from 2006 to 2009 can be used in REMix. The GIS data has a spacial resolution of 10 x 10 km^2. Energy demand and the weather data have a time resolution of one hour (Nitsch et al., 2010a). Additional restrictions for the use of renewable energy are included at the GIS data in terms of e.g.

population density, elevation of the terrain, and protected areas. While the conventional power production is reduced to only one category with the characteristics of a gas power plant, the electricity production by renewable energy sources is simulated for photovoltaic power, concentrated solar power, on- and off-shore wind power, biomass, hydro power, and geothermal power.

1) Solar power: The calculations of electricity production by PV is based on solar radiation data. This data was generated from remote sensing measurements by using the HELIOSAT-method (Hammer et al., 2003). An adaption of the photovoltaic efficiency for module temperatures differing from 25°C is calculated by using irradiance and ambient temperature data. Efficiency losses due to PV-module shading and dimming by dirt is considered with a correction factor.

The placement of PV-modules is subdivided into many different types like roof-tops or open land areas with a resulting fraction of usable area from less than 1 % up to 33 %.

For simulating Concentrating Solar Power (CSP) plants, only the direct solar radiation component of the data must to be used. REMix considers parabolic trough power plants with an adjustment in north-south direction of the troughs. To decouple the electricity generation from the moment of sunshine, a heat storage of a capacity for 12 hours of full load can be implemented to each power plant (Scholz, 2012). The ratio of installed receiver power at the solar field to the turbine and generator power can be scaled from one to three. This so called solar multiple is needed to obtain sufficient heat to operate the turbine and, if implemented, the heat storage for times of less irradiation. For the calculation of the electric power output loss factors for the generator, the heat storage and the efficiency of the solar receiver field are used. Since these types of power plants would be typically build in dry areas with a high share of direct solar irradiation such as the south of Europe and the north of Africa, both with a low population density, the model uses up to 33 % of this areas for the placement.

2) Wind power: To calculate the electricity generated by wind power, one hour averaged wind speeds from the COSMO-EU weather model (Schulz and Schättler, 2011) of the German meteorological service (DWD[2]) are used. The wind speed data are given for a heigh of 116 m above the ground. Since REMix uses hub heights of wind turbines between 112 m and 132 m (Scholz, 2012), the wind speed is scaled by using a logarithmic wind profile. To translate the wind speeds into an electricity output, the power curve of the E-82 turbine of Enercon is used (Scholz, 2010). Factors for additional losses and the availability of the turbines lead to the final electricity production by wind power. The model is allowed to use from 3 % up to 33 % of the area for the installation of wind turbines, depending on the area type.

Offshore wind turbines are treated almost in the same way as the onshore variant, but the hub height ranges from 80 m to 140 m (Scholz, 2012) and the factors for additional losses and the availability are modified. For the placement, 16 % of the offshore area can be used by the model.

3) Bio power: For the use of biomass, data of the national potentials from (Thrän et al., 2005) are used. REMix subdivides the usable biomass from wood over energy crops to secondary products and choose between three types of power plants with and without Combined Heat and Power (CHP).

[2]Deutscher Wetterdienst

4) Geothermal power: Geothermal power plants are considered for drilling depth of 2000 m down to 5000 m. The heat potential is taken from the Atlas of geothermal resources in Europe described by Hurter and Schellschmidt (2003). The installable power is calculated as a function of the usable heat per cubic kilo mere, which depends on the temperature difference of the extractable- and the re injected temperature. The system is seen as renewable under the premise that the heat can be extracted for a period of at least 1000 years. Like the bio power, the geothermal power can be used as well as combined heat and power to provide heat.

5) Hydro power: The placement of river hydro power plants is based on the 2007 Survey of Energy Resources of the World Energy Council (Zupanc et al., 2007). Europe's potential for the year 2050 is assumed to be 1100 TWh/a (Scholz, 2010). To calculate the temporal electricity production the daily averages of river runoff data of the Global Runoff River Database of 2008 are used.

To distribute the electricity around Europe a High-Voltage Direct Current (HVDC) grid is included in REMix. While the intersections of the grid are predefined as one per country, the capacity of the power lines is optimized by this model. The advantage of using HVDC lines, at least for distances longer than 500 km, is the small loss of around 3 % per 1000 km transmission (Trieb et al., 2009).

To deal with times of over- or underproduction of electricity, three types of energy storage technologies are implemented in REMix that can be used to level out the supply and demand. Pumped hydro power storage capacity is limited to the already existing plants in Europe except for Norway, where an additional potential of 70 TWh is assumed (Scholz, 2010). The proportion of energy storage capacity for pumped hydro power to installed generator power is 8 kWh:1 kW and the round-trip efficiency is 0.8. Compressed Air energy storage plants have a lower efficiency of 0.7, but the theoretical capacity is almost unlimited. Hydrogen is mainly used to store energy for longer periods because of its comparatively high energy density and the round-trip efficiency of 0.44 (Scholz, 2010). The capacity of storing energy with the use of hydrogen is almost unlimited as well.

2.3. The DICE and RICE model

The Dynamic Integrated Climate-Economy (DICE) model and the Regional Integrated Climate-Economy (RICE) model have been developed both by W. Nordhaus and his colleagues at Yale University (for a detailed description see Nordhaus (1992), Nordhaus (2010), Nordhaus and Sztorc (2013) and Newbold (2010), which are the main references for this section). They have been developed over a period of more than 30 years with many model versions in between[3].

These models are inter-temporal general equilibrium models of economic growth and climate change to estimate the optimal path for a reduction in emissions of greenhouse gases. Their major difference is the fact that the RICE model has regional structures in output, population, emissions, damages and abatement and are not globally aggregated as in the case of the DICE model. So, while DICE considers the whole globe as a unit, RICE started with a eight division but changed to 12 model regions defined

[3]On www.dicemodel.net the models are available as Excel and GAMS version.

as US, EU, Japan, Russia, Eurasia, China, India, Middle East, Sub-Saharan Africa, Latin America, other high income countries and other developing countries (Nordhaus and Sztorc, 2013). Below this structure there is no computing grid for the regions, since the models do not consider geographical distributions except externally given boundary conditions.

The time frame of about two centuries as considered by the DICE and RICE model for their calculations is quite large in contrast to most other models. Since climate change processes are relatively slow according to the authors, the time horizon of the scenarios is set to the year 2200 to allow the model a feedback of climate change on the economy.

For boundary and initial conditions the DICE and RICE models need a lot of external data regarding population, resources, potentials, capacities, demands, etc.

The dynamics of the DICE and RICE models come from the development of energy supply from different fuels and the energy demand of the represented sectors. The important point is that the models consist of two major parts, an economic and a geophysical sector. These sectors are linked by green house gas emissions on the one hand and costs of climate change on the other hand. So the model results can be interpreted as the most efficient economic path for slowing climate change (Nordhaus, 1992). In the following an overview is given of 1) the economic and 2) the geophysical sector of the models.

1) The economic sector is based on a modified Ramsey-style[4] optimal economic growth model, where an additional form of a natural capital, viz. the atmospheric concentration of CO_2, has a negative effect on the economic output. So the major choices are to consume goods and services, to invest in productive capital, or to slow climate change. To do this in an optimal way, the maximization of the discounted sum of the utility of per capita consumption is needed as it can be written in a general form of a so-called social welfare function

$$W_{max} = \max_{[c(t)]} \sum_{t=1}^{T} U[c(t), P(t)] \cdot (1+\rho)^{-t}, \qquad [2.1]$$

with U as the level of utility or social well-being, $c(t)$ as the flow of consumption per capital at time t, $P(t)$ as the level of population at time t and ρ as the pure rate of social time preference in terms of a discount rate for the welfare weights on the utilities of the different generations being involved. The maximum of the general equation eq.: [2.1] depends in the case of the DICE and RICE model on conventional economic constraints and emissions-climate-economy constraints (Nordhaus, 1992).

The use of maximization or optimization in these models should be seen as a first approximation to simulate the behaviour of a system of interacting competitive markets for describing the equilibrium state of a market economy. The output is measured as standard gross domestic product (GDP[5]) while converting all into US international prices. This way of pricing anything may not fit to all ethical norms

[4] The Ramsey problem results out of the theory of an optimal taxation in terms of a maximization of social welfare. This taxation of different goods depends on their price elasticity of demand. So the taxation needs to be lower if the consumers re-act very sensitively on the price of a good.

[5] GDP is a measure of the market value of all final goods and services that have been produced in a region within a certain period of time, which is typically one year. So the GDP per capita can be seen as an indicator of welfare.

but it represents the basic laws of supply and demand. To get this into standard welfare economics, additional ethical endowments have to be defined to make the outcome efficient and fair. Without that assumption, the results could only be seen as Pareto efficient[6].

The resulting policy for the DICE model belongs to the average individual as the whole world is treated as a single economy. In contrast, in the case of the RICE model, the world is actually separated into 12 different regions where each has its own social welfare function to define its specific preferences. This allows the RICE model to act with multiple agents in terms of regions and gives thereby a view on a national level of climate policies and strategies for international co-operation.

While the capital is calculated by the optimization of the model, driving influence factors such as technology change path or the population growth are given as exogenous. So, for the 2007 versions of the models, the population started at a level of 3.2 billion and reached with a growth rate that decreases slowly up to the year 2200, a value of 10.5 billion (Newbold, 2010). Following Nordhaus and Sztorc (2013), the newest version starts at the level of the year 2010 and its growth already stabilizes in 2100 at 10.5 billion people.

2) The geophysical sector is needed to represent the behaviour of the non-market items in the model. As mentioned above, the DICE and RICE model optimize the consumption over time not only for traditional market goods and services but for the non-market items like health and environment as well. This represents the second sector of the models, the climate-emission-damages which include emissions of green house gases, their concentrations, climate change, damages and mitigation costs. To realize a feed back of climate change on the economic part of the models, concentrations of green house gases can be seen as negative natural capital and investments on emission reductions as a rise in the quality of natural capital.

Basically climate change is represented for the DICE and RICE model in terms of global mean temperature. To estimate these temperature relations, current climate models are used.

The modeling of green house gas emissions, the carbon cycle, the resulting radiative forcing, the climate modeling in terms of global mean temperature rise and the climate damage relationships are realized as quite simplified structures based on the experiences of much more complex models. A clear advantage of the simplified modeling as part of the DICE and RICE model is that the modules can operate in an integrated way instead of requiring exogenous variables as input from other models.

Endogenous green house gas emissions of the DICE and RICE models are limited to CO_2 that is emitted by industry. Other emissions as occurring from land use change, sulfate aerosols and further non CO_2 green house gas emissions are given as exogenous. As additional restriction for the CO_2 emissions, there has been set a total carbon limit to 6000 billion tons (Nordhaus and Sztorc, 2013). All the emissions will lead to additional costs of climate change, but on the other hand, also actions of reducing CO_2 emissions have their own costs. So, in the newest model version, a carbon price can

[6]Pareto efficient means a situation where nothing can get further optimization without making at least one other worse.

be calculated explicitly and is determined by assuming that the price is equal to the marginal cost[7] of emissions. Also, the DICE-2013R model explicitly includes a backstop technology that is able to replace all fossil fuels. This could be for example, solar power, carbon-eating trees or a technology that has not even been discovered as yet. For the year 2010 the backstop technology starts with a price of 344 $ per ton of CO_2 at 100 % removal and declines with 0.5 % per year (Nordhaus and Sztorc, 2013).

To calculate the concentration of the climate relevant CO_2 in the atmosphere, a tree layer carbon cycle model has been integrated into the DICE and RICE model. It splits the environment into three different reservoirs. The atmosphere, where the CO_2 emissions goes to, the upper ocean and the biosphere and as third reservoir the deep ocean. Each reservoir is assumed to be well mixed in the short run with the deep ocean as a large sink for carbon in the long run. Now they interact in the way of a 100 GtC emission into the atmosphere, 35 % of which will remain there after 100 years (Nordhaus and Sztorc, 2013).

Knowing the CO_2 concentration in the atmosphere by the carbon cycle model, the radiative forcing can be calculated. This means considering the impact of the accumulation of green house gases in the atmosphere on the radiation budget of the globe. Based on this, the mean surface temperature on the globe and the averaged temperature of the oceans can be calculated for each time-step of the model run. For older model versions the sensitivity of the temperature on a doubling of the atmospheric CO_2 concentration was set to a warming of 3 °C considering an adjustment time of 19 years which means 63 % of the equilibrium temperature (Nordhaus, 1992). Now the climate sensitivity of the DICE and RICE models are not only based on results of general circulation models, but on additional sources such as historical record data as well. The weighted average of these estimates leads to a climate sensitivity of 2.9 °C for an equilibrated CO_2 doubling (Nordhaus and Sztorc, 2013).

The resulting damages at the DICE and RICE models from the above described climate change are subdivided into agriculture, sea level rise, other market sectors, human health, non-market amenity impacts, human settlements including ecosystem and catastrophes. For the RICE model additionally, all damages are specified for the individual model regions. The impact on the economy increases nonlinear for the climate change. Therefore a quadratic function has been implemented to make further climate change even more weighted comparing to the beginning. But as there are no tipping points well enough determined for climate change, the model does not consider any steps in the price function of temperature rise. Also the damage function for climate change has been calibrated for the range of 0 °C to 3 °C of temperature rise, which should be good enough for most climate scenarios. If a temperature rise much higher than 3 °C is to be simulated or even special catastrophic damages need to be part of the scenarios, the damage function needs to be re-specified.

As for the latest model version the DICE-2013R, the fifth assessment report of IPCC in 2013[8] already was available, the geophysical modules could be adjusted to the report. So the modeled climate, radiative forcing, carbon emissions in base line scenario, and much more, are largely consistent with the final IPCC

[7] Marginal costs are assumed to be the costs of generating one extra unit of a product or, in this case, costs resulting from an additional emission of CO_2.

[8] www.ipcc.ch/report/ar5

report. For the base line scenario it is meant to represents the outcome of market and policy factors as they currently exist or it would occur with the current climate-change policies. As an example, the damages in the baseline scenario for the year 2095 would be 12 trillion $ or 2.8 % of global output, by reaching a global temperature rise of 3.4 °C above the level of 1990 (Nordhaus, 2010).

2.4. The SEXPOT model

The Spatiotemporally-Explicit Power and Transmission (SEXPOT) model is a spatiotemporal linear programming model to simulate deployment of wind and solar power at high spacial and temporal resolution on a global scale. It was developed at the Central European University (CEU) and has been programmed in the open-source R programming language (Venables and Smith, 2014). A detailed description is given by Ummel (2011) which as well is the main reference for the following descriptions in this section.

The model is based on a variety of meteorological, geophysical and socioeconomic data. As output it offers preferred locations for using wind and solar power and how they could be used in combination with other technologies. Additionally it considers transmission lines and their routing from the places of electricity generation to the regions of demand.

In total the model considers on- and offshore wind power, PV, coal, gas, nuclear and hydro power plants to provide the demand for electricity.

For the calculations of solar and wind power, SEXPOT makes use of global reanalyzed meteorological data from the Modern-Era Retrospective analysis for Research and Applications (MERRA) project (Lucchesi, 2012). The model makes use of the wind speed at 2 m, 10 m and 50 m above ground, the solar radiation on the ground and the air temperature and humidity at a level of 2 m above the ground. This data has a time resolution of one hour and covers the year 2006. The spacial resolution of the grid is 0.67° times 0.5°. To estimate the spacial and temporal distribution of electricity demand all over the globe, a statistical model has been implemented. This uses night time satellite images for the year 2006 to calculate the distribution, and predicts how demand changes depending on the time of the day and the weather conditions as the ambient temperature. To consider geographical restrictions for the placement of power plants and transmission lines, land cover data mainly from dataset developed by the European Space Agency and the Universety catholique de Louvain of 2009 are used. Most of this data has a spacial resolution between 300 m times 300 m and 1 km times 1 km. The data reach from land cover, terrain slope, population density, geomorphology, elevation and bathymetry, lakes and wetlands, lake depths, protected areas and rooftop area up to travel time. As economic input for the optimization by the model, assumptions about costs of the power technologies, fuels, the efficiency of transmission lines and CO_2 emissions by coal and gas power plants have been defined.

Seeing that SEXPOT is a global model, its spacial and temporal resolution leads to a huge amount of variables that would have to be considered for the optimizing part of the model. To reduce this data to some thousands of variables for the cost function, the 8760 hours of a year have been reduced to only

288 hours per grid cell variable. This 288 represent for each month of the year one mean day with a hourly resolution.

The optimization itself can be done for a demand supply at minimum costs with optional constraints for CO_2 emissions or a minimized penetration of renewable technologies, while considering as well expected growth of electricity demand and retirement of aging power plants. As SEXPOT only recognizes one sector, the electricity supply, it can not be used as a complex policy model but to investigate on distributing of electricity infrastructure.

1) Wind power: The wind power sector is represented at the model by turbines at a hub height of 80 m above ground for onshore and 120 m for offshore wind power. To calculate the wind speed at the hub heights, the model fits a power law function on the wind speed data of 2 m, 10 m and 50 m above ground. The power curves of the wind turbines are represented by a logistic function that has been fitted to multiple power curves. Additionally, losses of around 10 % of the electricity output are assumed and a power correction for the air density is considered as well.

2) PV power: For the simulation of PV-cells, the global radiation data is separated into its diffuse and direct radiation parts by using the method of Ridley et al. (2009) with multiple predictors. Efficiency losses of the pv cells due to temperature is modeled as well and the performance of the inverters is done in the way of King et al. (2007). To calculate the potentials, the model chooses for each location the optimal tilted angle for the PV-modules and, as reference, a thin-film of CdS/CdTe semiconductor PV type has been used.

3) Gas, coal and nuclear power: The conventional gas, coal and nuclear power plants are quite poorly represented, as they do not even consider ramp on and ramp off behaviour. Additional gas power plants are considered as backup technology for the variable electricity generation by wind and solar power. This is needed to allow the linear programing optimization routine to meet peak demand under average electricity generation conditions. However this assumption still leads to an underestimate of the required reserves.

4) Hydro power: For the development of hydro power, the model has an estimated limit for the maximum annual output based on data of 2007. This is needed to prohibit an extreme expansion of this relatively low priced technology.

The distribution of the electricity supply is driven by the assumption that land based projects require a city of at least 50,000 people that could be reached within three hour drive on paved roads. For the placement the model has to consider the above mentioned land use data and results with a 10 km grid resolution for the positioning of the power plant technologies. For the placement of offshore projects, a maximum distance of 100 km from coast is allowed.

Electricity need is driven by the demand curves of 26 electricity markets of Europe and Australia combined with an statistical approach. So a multivariate adaptive regression spline is used to predict mean hourly load and the maximum peak load depending on weather and daytime for the representative 288 hours that are used for the optimization.

Even after the data reduction in time a regional reduction is needed as well before the optimization can start. The algorithm select a subset of potential renewable energy sites and consumption centers that are supposed to give results similar to that of an unconstrained model. Having these representative nodes, the economical production and use costs, the costs for transmission and emission saving can be considered by the linear programming optimization algorithm.

The routing of transmission lines is done as well on a 10 km wide grid. It includes geographical restrictions, power losses with 1 % per 100 km (Ummel, 2011) and transmission costs.

For the optimization, the objective function that specifies the total cost of providing electricity needs to be minimized, recognizing a set of linear constraints. The total costs depend on capital costs that are associated with building the facilities, variable costs for generating electricity and the cost of transmission. Data about the prices, and for CO_2 emission rates as well, have been taken from the US annual energy outlook 2010. A discount rate of 7 % is used and the project lifetimes are between 20 to 40 years. Additional constraints can be given on land use, demand, CO_2 restrictions or a minimum share of a specific technology depending on the defined policies. Based on data from the 2010 world energy outlook, SEXPOT predict the electricity consumption up to year 2035 for future scenarios.

2.5. The SimEE model

The model for simulation of the feed in of renewable energy (SimEE)[9] was developed by the Fraunhofer IWES and is continuously enhanced. It focuses on a detailed representation of the technical characteristics of electricity producer, consumer and storage systems. So an analysis of the German electricity supply system can be done by SimEE for varying scenarios, while regarding the needs for supply and demand of electricity. A detailed description of SimEE can be found in Nitsch et al. (2010b) and (Nitsch et al., 2010a), which is also where the main references for this section can be found.

The electricity demand for the simulations is given by data from the European Network of Transmission System Operators for Electricity (ENTSO-E) as hourly mean values of the load for Germany since 2006. Depending on the total consumed energy of the observed scenario, the demand curve will be scaled to fit the annual electricity demand. Additionally the electricity demand at SimEE can be adjusted by load management, taking technologies such as electric cars, electric heat pumps and cooling systems into account.

To provide the needed energy, SimEE offers a wide variety of renewable energy technologies and one type of condensation power station, to deal with the residual loads in the way of any modern gas power plant. For the simulation of the non controllable renewable energies SimEE uses weather data for Germany with an spacial resolution of 14 x 14 km^2 and a temporal resolution of one hour (Nitsch et al., 2010a). To get an approximate idea about the inter-annual variations in energy production by renewable energy, the meteorological data cover four years from 2006 to 2009.

[9]Simulation der einspeisung Erneuerbarer Energien

1) Wind power: To calculate the hourly electricity production of wind power, SimEE uses wind speed data from weather reanalysis by the COSMO-EU model of the DWD (Schulz and Schättler, 2011). With the use of wind turbine power curves, the corresponding electricity output per wind speed can be calculated. Effects on the energy output like park shading are taken into account as well, while calibrating the model by using time series of the electricity output of existing wind parks. The positioning of the wind parks in SimEE is oriented to Germany's 2009 stock and, in addition, an expansion plan for scenarios with a higher capacity of wind power. Offshore wind turbines are considered in a similar way, but with additional 4 % losses for the transmission of the power back to the coast.

2) PV power: The calculation of the electricity generation by PV is based on the horizontal global solar radiation of the Helioclim-3 dataset. For dealing with the reduction of PV-cells efficiency by increasing temperature, SimEE also uses data of the air temperature from the DWD. A statistical approach, based on the German PV stock is used, to consider different types of PV-modules, their orientations and their angle of installation for the simulation of PV output. To consider the behavior of the inverter modules, the model of Beyer et al. (2004) is used. The placement of the PV for the scenarios is oriented on data by the German law on renewable energies (EEG)[10] for the German pv stock. Additional placements are calculated by the population density and the solar radiation.

3) Hydro power: The hydro power energy production is driven by data of daily mean river flow rates for all sites, where in the year 2004, power plants greater than 1 MW of installed power were used in Germany. The power output is scaled to the annual demand of the investigated scenario and, due to the reason of shipping, storage power plants are assumed as non adjustable at SimEE.

4) Biomass power: The use of biomass is coupled to the heat demand calculated by weather data. Here biomass power plants are subdivided into non adjustable heat driven and electricity driven plants using timber as fuel in addition to adjustable bio gas power plants. Hot water storage devices help to increase the flexibility of using the bio power plants.

5) Geothermal power: The geothermal power plants are subdivided as well into heat driven and base load plants driven by electricity. During the summertime, when less heat is needed, the electricity portion of the geothermal power can be increased.

To achieve the balance of energy demand and production, in a supply system with a high share of fluctuating renewable energy sources, additional options to the bio and geothermal power plants are needed. The use of these options is driven by a load-dependent cost function, where the cost optimised strategy is analyzed by an iterative planning process during the simulations with SimEE. So electric heat pumps, air conditioning systems and electric cars can be used to shift loads within a couple of hours. In the range of the heat retention within buildings, the electricity demand on heat pumps and air conditioning can be uncoupled such as keeping the temperature of the rooms at the required level. In addition, the charging of electric cars can be managed to adjust energy demand to the supply in a certain range. The use of the batteries of the cars as storage is not considered at SimEE. To simulate the way

[10] Erneuerbare-Energien-Gesetz

cars are used, an average working day plus Saturday and Sunday was taken of a study by the German Bundesministerium für Verkehr (Follmer et al., 2003). For Scenarios for the year 2050 it is assumed that all electric cars will have a connection to the electricity grid at their parking places.

If even after the process of load management, there is still excess electricity or a deficit, storage systems will be used as the last instance. For short time storing, both pumped hydro power and compressed air energy storage power plants are implemented to SimEE. To store energy over the seasonal variations, hydrogen and methane technology is used, because of their high energy density.

SimEE offers the opportunity of coupling it with the model REMix of the DLR, so that the model region Germany can exchange its electricity with the European grid of REMix. This leads to additional adjustment effects for the energy demand and supply including effects on the power plant setup for the simulated scenarios. The models SimEE and REMix interact in two iteration steps, where their time series of energy production and demand is exchanged and adapted for optimizing the import and export of the energy supply.

2.6. ’Model for combining wind and solar power’

As no name has been given to the electricity supply model presented in articles like Heide et al. (2010), it is described here as a ’model for combining wind and solar power’. It only focuses on the combination of PV and wind power as electricity supply for Europe without any economic assumptions. The design of the model allows investigation into the residual load in terms of needed electricity storage or backup power plants resulting from an electricity supply only based on wind and or PV power plants. Further details on the model can be found in von Bremen (2010), (Heide et al., 2010) and (Heide et al., 2011), which are also where the references for the explanations in this section can be found.

The model covers a time range for its calculations of eight years from 2000 to 2007 by providing a temporal resolution of one hour. Its model region is defined for Europe including offshore regions and the spacial resolution is given by the weather data to 47 km times 48 km.

To calculate the time series of potential electricity generation by using wind and PV power, the model makes use of meteorological data from Weather & Wind Energy Prognosis (WEPROG). This data is based on weather data from the US weather service NCEP (National Center for Environmental Prediction) and has been downscaled by using a regional weather model. For the calculations of wind speed at 100 m above the ground, net short wave solar radiation at the surface, total cloud cover and a standard albedo for clouds and the surface are used.

The positioning of PV and wind power plants is predefined by making use of the expected capacities to be installed at Europe in 2020 based on the national targets for renewable energies. This plants total to 227 GW of wind and 68 GW of PV power capacity, while 66 GW of the wind power plants is assumed to be installed offshore (Heide et al., 2010). The finer distribution of the power plants on the grid cells of the weather data is done empirically, giving more capacity to those grid cells with higher potentials. To allow a wind only scenario, the 227 GW needs to be upscaled by a factor of 5.2 to generate the annual electricity demand. In this case the wind power works with 2650 full load hours (Heide et al., 2010). For a PV only scenario an upscaling by a factor of 25.5 is needed to generate enough electricity. Here the PV power plants work with 1800 full load hours (Heide et al., 2010), which seems to be quite high.

1) Wind power: To simulate the electricity generation by wind power plants, the model uses typical wind power curves at 100 m hub height for both onshore and offshore. For the case of the offshore wind power, wake effects for a seven times seven wind park layout is considered. Additional losses of 7 % for generator and non availibility has been assumed for all wind turbines.

2) PV power: The simulation of PV power is done by considering the air temperature for the efficiency of the PV modules and the global solar radiation, calculated from the data of net short wave solar radiation at the surface, total cloud cover and a standard albedo for clouds and the surface. For the PV power plants, a mix of different PV plants per grid cell in terms of tilted angle, orientation, with and without tracking systems is assumed.

On the electricity demand side, the model uses data of load profiles for almost all European countries that have been summed up and leveled to an European load curve.

Once all time series for wind and PV power of the approximately 2600 grid cells of the 27 European countries including offshore regions (Heide et al., 2011) have been calculated, the output of the required power plant capacities will be aggregated to one supply curve. This is done under the assumption of a perfect transmission grid for Europe, where the electricity is available everywhere in the model region without any restrictions or losses.

Having the time series for wind power $W_{(t)}$, PV power $S_{(t)}$ and the demand $L_{(t)}$ the hourly mismatch in electricity supply is calculated by the model using

$$\Delta_{(t)} = \gamma \cdot [a \cdot W_{(t)} + (1-a) \cdot S_{(t)}] - L_{(t)} \qquad [2.2]$$

(Heide et al., 2011). With the parameters $a \in [0,1]$ denoting the share of wind power generation of a wind and PV power supply and $\gamma \in [1,2]$ to simulate excess electricity generation by wind and PV power in addition to the minimum required electricity at $\gamma = 1$. The resulting mismatches in electricity supply of eq.: [2.2] have to be compensated by charging or discharging energy storage units each with its own specific efficiency. Alternatively, the balancing can be assumed to be done by backup gas power plants instead of energy storage systems. In this case the positive mismatches are wasted and the negative mismatches require gas as fuel.

2.7. The World Energy Model (WEM)

The World Energy Model (WEM) was developed by the International Energy Agency to provide medium and long-term energy projections on a global scale. While doing this, its focus is set to replicate the behavior of energy markets. So it can be seen as a tool to generate detailed sector-by-sector and region-by-region projections for various scenarios. The model is described in details by International Energy Agency (2011), where the main reference for the section can be found as well.

Currently, it is the 15th version of WEM and the model is based on six main modules: final energy consumption, power generation and heat, refinery, fossil-fuel supply, CO_2 emissions and investments. To run the model, a huge amount of data is required and much is obtained from the IEA's own databases of energy and economic statistics. This database is also recognised as one of the world's most authoritative energy statistics (International Energy Agency, 2011).

As the WEM covers the whole globe, it has a division of 25 regions of which 12 are single countries and 13 cumulated regions. A detailed list of the defined regions can be found in the appendix of International Energy Agency (2011). The structure of the regions is defined by their individual constraints, but there is no underlying grid to define distributions of, for example, potentials or needs inside the modeled regions. Regarding the temporal resolution of the WEM, the calculations are done on a one year scale and the time horizon typically ranges up to the year 2035. So the model is mainly designed for global energy prospects, environmental impacts of energy use, effects of policy actions as well as for technological changes and investments in the energy sector.

The WEM is a large-scale mathematical construct and it makes use of a wide range of software in terms of specific database management tools, econometric software and simulation programmes. Driven by the databases, the main exogenous assumptions of the WEM concern economic growth, the behavior of demographics, international fossil fuel prices and the development of technologies. The model module for the demand-side estimate the requirements to be provided econometricly by using data from 1971 to 2009. Rates of population growth come from the United Nations Population Division report and lead to an averaged increase for the population of 0.9 % per year. So simulations start with a population of 6.8 billion people in 2009 and end with an slowing growth at 8.6 billion in 2035. For the economic growth it is assumed for each model region to converge into an annual long-term rate.

As final energy demand, the WEM differs for at least six types: coal, oil, gas, electricity, heat and renewables. This demand occurs for industry, residential, services and transport. It is a function of activity that is measured as GDP per capita and end-use prices that is counted in US Dollars per tonne of oil equivalent and additional variables such as saturation effects or technology changes.

The quite energy intensive industrial sector of the WEM is split into iron and steel production, the chemical and petrochemical industry, industry using non-metallic minerals, paper production and other industries. The energy consumption is calculated on the base of their products output. While measuring the need for energy per unit of output, the output itself is calculated on an econometric basis with an input of experts judgment.

For the transport sector, the model accounts for transportation on roads, rail, by air and sea. The activity in transportation per region is modeled as a function of population GDP, fuel costs per km and CO_2 emissions. The dependency on the fuel costs leads to an interest on increasing efficiency and alternative fuels. So, for example, the road model supports all types of fuel cars like hybrid, full electric, hydrogen fuel and biofuels. The biofuels are specially represented by an own cost tool.

In terms of residential, the WEM distinguishes between OECD and non OECD areas. The energy consumption of the residential sector is driven by the use of space heating, water heating, cooking, lighting and appliances. At this sector, the intensity of energy use depends on the end-use-price but also the standard of living within a region, the size of housing and many other variables are used to identify the demand for energy.

To simulate the supply with sub products of oil in terms of light, middle and heavy products, the refinery module estimates a base case refinery output for all model regions. Therefore the module requires past domestic demand and the region's share in global trade of oil products. The estimations for the future are orientated on existing projects and data from BP gas and oil journal as well as from the IEA oil market report. An optimization process controls the balancing for the supply and demand, while considering costs per unit, environmental, capacity and political constraints.

Power plants for the supply of electricity and heat are treated at the WEM in the way that, first the number of required new generating capacities to counter the growing demand and the retirements of old plants that need to be calculated year by year. Then, knowing the required capacity, the type of plant technology to build has to be chosen depending on the expected way of use and costs. The power plant module also calculates the amount of electricity generated by each type of plant to meet the demand of electricity in each region including own use of the plants, transmission and distribution losses. But the power plant capacity also has to meet the annual peak electricity demand. Another outcome is the fuel consumption by the power plants and last but not least the electricity price that results from the used power plants.

At the beginning the model uses the existing capacities known from a database of all world power plants. The age of each power plant and their expected live time, which is assumed for fossil and nuclear to be 45 to 60 years, 20 for wind and PV, 50 for hydro power and 25 for bio power, needs to be considered to build new capacities. In the case of power plants using volatile renewable energies, a capacity credit is estimated from historical data on hourly demand and generation from the variable renewables in a number of electricity markets. This reflects the proportion of their installed capacity that can reliably be expected to be generating at the time of peak demand.

When new plant capacities are needed, the choice between different technology options is done on the basis of their regional long-run marginal costs. The costs depend on the merit order of the power plant mix on the market, their utilisation rate and some minor facts. Plant types that are supported by the WEM are coal, oil and gas steam boilers with and without Carbon Capture and Storage (CCS), combined-cycle gas turbines with and without CCS, open-cycle gas turbines, integrated gasification combined cycle power plants, oil and gas internal combustion power plants, fuel cells, biomass, geothermal, on- and offshore wind power, hydro power, PV, CSP and marine power in terms of tide and wave. All fossil fuel and biomass plants have the option of a combined heat and power use. Nuclear capacities are not a subject of the choice by the market model, they belong only to government policies. The deployment of renewable energies is based on an assessment of the potential and cost by each source in each of the

25 model regions. The investments on renewable power plants are coupled with dynamic cost reduction curves. This means a static cost reduction as a relationship between a) available potentials and costs of utilisation of this potentials and b) a dynamic cost assessment by technological learning. Also dynamic restrictions that are applied to the predefined overall long-term potentials in terms of market constraints and technical barriers like grid constraints define the costs of making use of renewable energies.

The electricity demand on the other side depends on various factors. The electricity price is a driving force, but also the need for electricity services, the income of households and the possibility to switch to other energy sources are used to calculate the electricity demand. Looking on the possibility to switch to other energy sources, the long-term price elasticity of electricity is very low as it is hard or even impossible to substitute this highly valuable form of energy. To summarise, the major driver of electricity demand in all regions is the economic activity.

For the transmission and distribution of electricity, the WEM uses a relationship between network growth and costs. But also the ageing of the infrastructure and additional costs associated with integrating renewables are considered. The additional costs for the integration of the renewables is based on the assumption that they can be widely distributed and their positions might be further from the consumer than conventional fuel based power plants.

A submodule added to the WEM in 2011 allows subsidies for renewable energies to be considered. This module uses the difference between each technology's long-run marginal costs in Dollar per MWh and the wholesale price of electricity per MWh. Doing this for each year of the power plant's specific lifetime and then multiplying by the capacity installed leads to the subsidies needed in a region for the specific technologies. The sum of all gives the total support required for renewables globally over the stated period.

Emissions are treated at the WEM as energy related CO_2, which accounts for the, by far, biggest share of anthropogenic global greenhouse gas emissions. So one of the important outputs of the WEM is a region by region CO_2 emission from fuel combustion that are calculated by multiplying energy demand with an implied CO_2 content factor. Those factors have been calculated as an average of the years 2007, 2008 and 2009 for all regions and are assumed to remain constant over the projection period. Additionally, the WEM considers emissions of SO_2, NO_x and fine particulate matter. A sub-module for the carbon flow has been implemented to take into account the 450 ppm atmospheric CO_2 concentration scenario. The model makes use of an economic trade theory applied in the context of climate change, where it uses marginal abatement cost to represent the cost of abating CO_2 emissions in a given sector. These marginal costs will rise with the amount of abatements and allows for country- and sector-specific abatement curves as well.

The fossil fuel supply is divided into oil, gas and coal supply models. The oil model uses a historical series of production and decline rates of oil fields by countries. The decisions of the model for developing of new reserves are based on the criteria of the net present value[11] of future cash flows. For the production the model makes use of the options of currently producing fields, production from discovered fields including those awaiting development, production from fields yet to be discovered, production of natural gas liquids and production of unconventional oil. Constraints on how fast projects can be developed and how fast production can grow in a given country are also applied. Gas supply is treated in a quite similar way as oil, but while oil is assumed to be freely traded globally, gas needs to be primarily regionally traded, with inter-regional trade constrained by existing or planned pipelines. The coal supply considers production, imports and exports based on demand projections and historical data on a country to country basis.

Regarding investments inside the WEM it divides supply- and demand-side investments and covers the period from 2011 to 2035. The investment needs for new capacity are based on projected supply trends, estimated rates of retirement of the existing supply infrastructure and declining rates for oil and gas production. The investments on the demand-side are driven by transport, electrical appliances in residential and services sectors, fuel burning equipment in residential and services sectors, electrical equipment in industrial sectors and fuel burning equipment in industrial sectors. In all the cases the trade-off for the investment in more efficiency, which reduces the demand of energy, has to be considered. So the model outputs includes the additional annual capital needs and the impact of the energy savings on the consumers' bills.

2.8. Summary of energy models and outlook for the MEET model

After the brief overview of the major representative energy models in the sections above, an important difference occurs that separates the models into categories (see also the summarising tab.: 2.1). The models focus either on a detailed description of the energy market's economics or on the physical behaviour of joining energy demand and supply together. The physical supply models typically consider regional distributed potentials for renewable energies, usually based on weather data, such as wind speed, solar radiation or air temperature, for at least a period of one year with a temporal resolution of one hour for their simulations. As this often leads to a huge amount of data and because some major variations in electricity supply occur during any year, this time period is used as a typical time horizon for the simulations. Contrariwise, economic models have to reduce the data in space and time due to their effort to simulate energy markets in an optimised way in order to find a development path over some decades for the energy scenarios. Therefore, these models often assume regions without an underlying model grid and solve the energy supply only on an annual time step basis. Many processes explicitly calculated by physical models are parameterised for the economic models.

[11] The net present value makes investments at different times and of different duration compatible as the investments are all discounted to their starting point.

Having both, the economical and the physical models, one can investigate the impacts of political restrictions on the development of a possible future energy market or the possibilities and needs for a future electricity supply system, especially when it is based on fluctuating renewable energies.

One of the major aims of this thesis is to provide an general overview on the behaviour and interaction of different power plant types being involved in an electricity supply system. The focus is set to an electricity supply by using renewable energies as it is required for the future due to limited resources and climate change. Wind and solar power are supposed to become the main renewable energies in electricity generation (Heide et al., 2010) and their volatile electricity generation will require energy storage systems. Thus, it is important to show the relationship between wind and solar power as well as storage systems in order to meet electricity demand.

The existing economic models such as GREET, RICE or the WEM are not adequate to investigate the mentioned relationship for electricity supply. Basically this models work on prise assumptions and political restrictions to show how an electricity system develops over the centuries to evaluate climate, political and market strategies. The electricity supply itself is models in a parametrized way on an annual base without simulating the detailed interaction of power plants.

Most physical models that calculate the electricity supply on an one-hour base, such as REMix, SEX-POT or SimEE, are not adequate as well. Of course, this models simulate the electricity supply quite detailed and sufficient, but still their decisions for the power plant mix base on an optimisation of prices and political restrictions given as scenario to the models. Therefore, the model results are highly dependent on the price development and the set-up of the scenarios can be complex. When thinking about, for example, the price development or learning curve of PV modules with its volatile decrease (Arvizu et al., 2011), it is obvious how fast such an optimum can change. Only the 'model for combining wind and solar power' described in section 2.6 offers the user to simply define a mix of wind and PV power plants in order to see how much power plant and storage capacities are required by the model. However, this model is limited to the region of Europe and offers just wind and PV power plants for the scenarios.

The Meteorological based Energy Equilibrium Testing (MEET) model was developed as part of this thesis in order to enable the investigations of the mentioned topics. The advantages of the MEET model are: It covers the whole globe. Continental regions are pre-defined and it is possible to define individually tailored investigation regions. Eleven years of weather data enable a sensitivity for inter-annual variations. In order to provide a wide range of electricity supply options, it is also possible to choose among ten different power plant types. Thus, the MEET model enables to define easily electricity supply scenarios by entering the power plant shares in order to work out the boundary conditions as well as the requirements of electricity supply independent from estimated price developments. It is possible to use this range of options and relationships, for example, to improve the electricity supply simulation in economic models. A detail description of the MEET model is presented in the section 3.

Table 2.1.: Energy supply models.

Energy model	GREET	REMix	RICE	SEXPOT	SimEE	Wind and PV	WEM	MEET
Area	Global	Europe and north Africa	Global	Global	Germany	Europe	Global	Global
Regions	11	11	12	-	-	-	25	7
Grid	No	10 x 10 km	No	10 x 10 km	14 x 14 km	47 x 48 km	No	2.5° x 2.5°
Prog. language	GAMS	C/GAMS	Excel/GAMS	R	-	-	-	Fortran 90
Type / focus	Economic	Supply	Economic	Supply	Supply	Supply	Economic	Supply
Cost optimised	Yes	Yes	Yes	Yes	Yes	No	Yes	No
Time step	5 years	1 hour	1 year	1 hour	1 hour	1 hour	1 year	1 hour
Time horizon	50 years	1 year	200 years	1 year	1 year	8 years	25 years	1 year
Weather data	-	4 years	-	1 year	4 years	8 years	-	11 years
Power plant types	12	8	-	7	7	3	20	10

3. The MEET model

In this section, the Meteorological based Energy Equilibrium Testing (MEET) model will be presented. MEET was developed at the Institute of Environmental Physics of the University of Heidelberg as part of this doctoral thesis, which belongs to a research project by the Heidelberg Center for the Environment (HCE) on global energy supply. From the basic assumptions, the input data, and the way of calculating electricity generation by the represented power plant types to the balancing of energy supply and the model output, the MEET model will be explain in the following sections.

Within the same HCE-research project, a second model called the Global Resource Extraction and Energy Transformation (GREET) model (Grogro, 2012) was developed by the doctoral candidate Ole Grogro of the Institute of Environmental Economics Heidelberg and the Zentrum für Europäische Wirtschaftsforschung (ZEW) Mannheim (for details on GREET see section 2.1). While the GREET Model covers the economical development of the energy market and the use of fossil energy carriers over a period of decades with a temporal resolution of five years, the MEET model focuses on the electricity sector of the energy supply with a simulation period of one year at an hourly resolution in time. So MEET and GREET complement each other in their considered simulation period, temporal resolution and details of simulating the energy supply.

3.1. The structure of the MEET model

The Meteorological based Energy Equilibrium Testing (MEET) model is a bottom-up computer model for electricity supply simulations written in Fortran 90. It is designed to investigate electricity supply strategies and principal effects on electricity supply by simulating renewable energies using power plants and fuel fired power plants all over the world.

Models are often designed for an economic optimisation of an energy scenario. These models are dependent on the assumptions on prices of the technologies for the electricity generation. In contrast, the MEET model has no cost optimisation, so that it allows the investigation from a physics perspective.

Any scenario with a combination of up to ten different power plant types to investigate the behaviour of electricity supply and energy storage requirements can be easily defined by the user. To do so a separate file called ’run_file.txt’ is provided where all specifications for the electricity supply scenario can be made for the MEET model (for a detailed explanation see section 3.19 and appendix B.1). The power plants offered by the MEET model for the electricity supply reach from full controllable to full weather dependent (tab.: 3.1). As totally weather-dependent electricity producers, offshore and onshore wind power, wave power and photovoltaic (PV) power are considered. The Concentrating Solar Power

Table 3.1.: Power plant types available in the MEET model.

Power plant type	Degree of control
Onshore wind power	Full weather dependent
Offshore wind power	Full weather dependent
Ocean wave power	Full weather dependent
Photovoltaic power	Full weather dependent
Concentrating Solar Power	Weather dependent but partial controllable
Runoff water power	Seasonal variation
Bio-fuel power	Full controllable
Nuclear power	Full controllable
Coal power	Full controllable
Gas power	Full controllable

(CSP) plants are controllable within a certain range. For base load by renewable energy, runoff water power is implemented in the MEET model. Bio-fuel power and the nuclear power, coal power and gas power plants represent the full controllable plants in the MEET model.

Geographically the MEET model is subdivided into seven model regions covering the whole globe, but the user can define an individual region as well. The horizontal spacial resolution of the model grid is 2.5° latitude and longitude.

The temporal resolution of the MEET model is one hour for a typical simulation range of one year. This is dictated by the resolution of the weather data.

The basic setup of the MEET model is given by the flow diagram in fig.: 3.1. It can be divided into two major parts:

1) Calculation of potentials for weather dependant renewable energy power plants for all grid cells.

2) Simulation of electricity supply.

This separation allows to save computation time when simulating multiple supply scenarios for the same weather data.

A run of the MEET model, starts with reading and preprocessing all data required for the simulation of the designed scenario. Then the MEET model calculates the electricity that could be generated by the weather dependant renewable energy power plants for each hour of the modelled time period on any grid point (i.e. the energy potential). After the potentials are calculated, the grid cells of each region get ranked for each power plant type starting with the highest energy potentials. Based on the ranking, the MEET model site the power plant types that have been defined by the user for the supply scenario to the grid cells. The time series of not controllable power plants, are then compared with the individual calculated electricity demand of the model regions. If there is a mismatch of electricity supply and demand, the MEET model has the option, if selected, to do some load management by shifting a defined range of loads within a defined range of hours and charge management of electric cars. Also CSP and bio-fuel power plants are taken into account followed by the nuclear, coal and gas power plants. If the power plants are not able to meet the demand or if they are not available for the defined scenario, energy storage is used by the MEET model as last instance to compensate deficits or excess in electricity supply. In case there remains a deficit due to lack of stored energy, the MEET model adjusts the amount of all installed power plant capacities correspondent to their defined share in the given supply scenario and tries to meet electricity demand again. After the required amount of capacities for electricity supply has been found by the MEET model in an iterative process, the fossil fuel CO_2 emissions are calculated and the output data will be written to the hard disk.

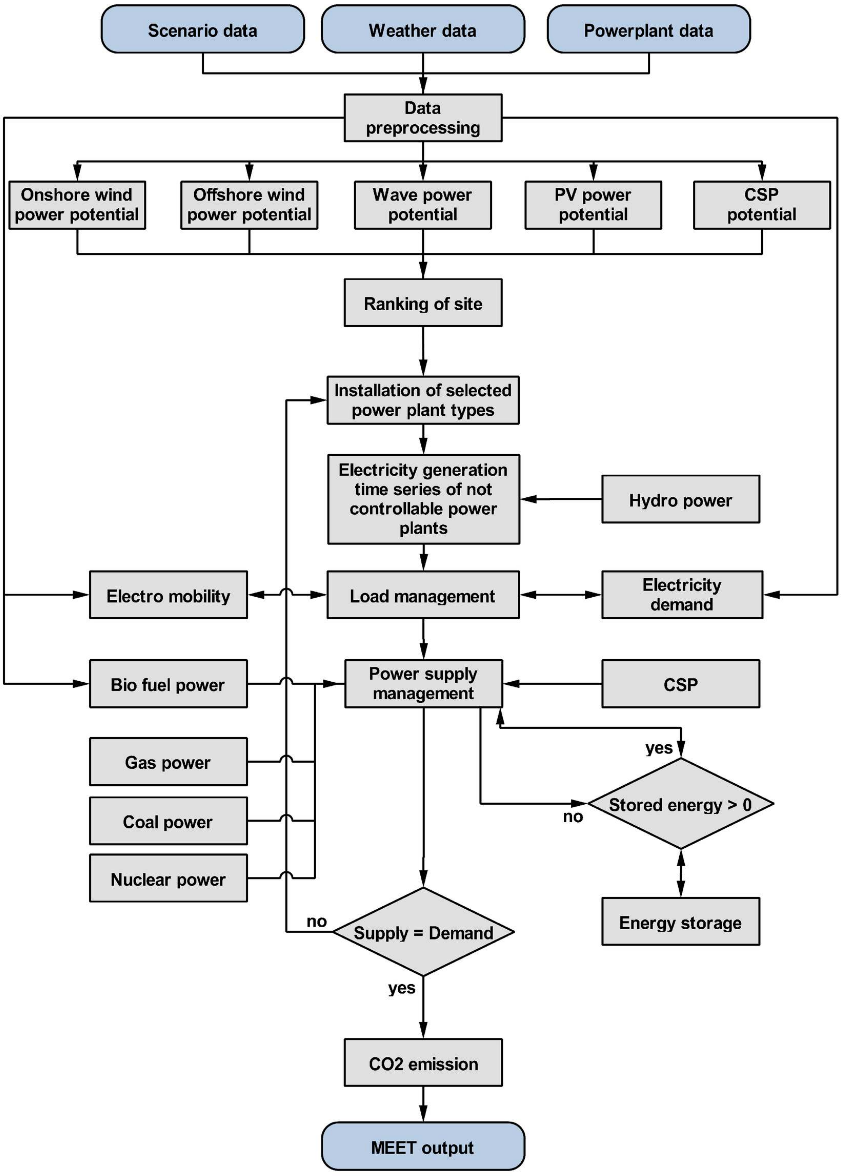


Figure 3.1.: Flow diagram of the MEET model.

In the following sections, the above mentioned procedures will be explained in detail starting with the model regions (3.2) and their electricity demand (3.3) followed by a description of the power plants (3.4 to 3.11), the ranking of potentials (3.12) and placing the power plants (3.13), the electricity generated by the power plants (3.14). To meet electricity demand, the load management (3.15) the power supply management (3.16), the optimising of the required power plant capacities (3.17) and the option of excess power capacities (3.18) will be presented. Finally the required data (3.19) and the assumptions for the MEET model (3.20) will be shown and an overview of the model output (3.21) is given.

3.2. Model regions

The model regions of the MEET model are mainly determined by the geographical borders of the various continents with the exception of the separation of New Zealand from Australia. So the seven regions of the MEET model are Asia (1), North America (2), Europe (3), Africa (4), South America (5), New Zealand (6) and Australia (7) (fig.: 3.2 in section 3.20). New Zealand comes as separated region, since it is not close enough to Australia to combine the two countries efficiently. Iceland is not considered because of its relatively small electricity demand together with its exposed position compared to Europe. A detailed list of the countries considered for the model regions is given by tab.: 3.2 and for further definitions of aggregated regions see also at BP (2009).

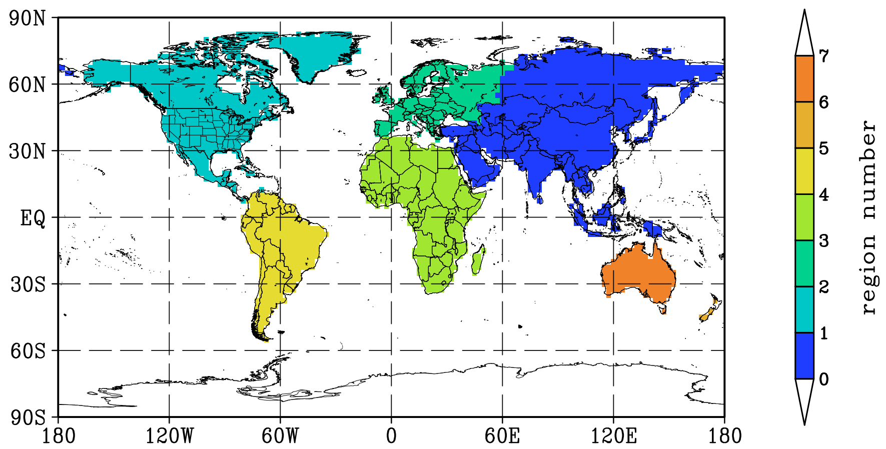


Figure 3.2.: Model regions of MEET.

The seven regions have been defined in a Geographical Information System (GIS) and then exported to a txt-file. This txt-file, as used by the MEET model assigns the 2.5° by 2.5° large model grid cells to the corresponding model region. If borders of a region going through a grid cell, the grid point is assigned to the region covering the widest part of the 2.5° grid cell. Also a 100 km buffer at the coastlines is taken into account for the model regions. This is needed for the offshore wind and wave power. In addition to the file representing the mentioned model region definitions that is used as standard for this thesis, the

Table 3.2.: Countries of the model regions for the MEET model

Model region	No.	Countries
Asia	(1)	Bangladesh, China, China Hong Kong, India, Indonesia, Iran, Japan, Kazakhhstan, Kuwait, Malaysia, Pakistan, Philippines, Qatar, Russian Federation, Saudi Arabia, Singapore, South Korea, Taiwan, Thailand, Turkey, Turkmenistan, United Arab Emirates, Uzbekistan, Other Middle East, Other Asia Pacific
North America	(2)	Belize, Canada, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panamá, United States
Europe	(3)	Austria, Azerbaijan, Belarus, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Republic of Ireland, Romania, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, Other Europe
Africa	(4)	Algeria, Egypt, South Africa, Other Africa
South America	(5)	Argentina, Brazil, Chile, Colombia, Ecuador, Peru, Venezuela, Other South America
New Zealand	(6)	New Zealand
Australia	(7)	Australia

MEET model has a second file which allows use of the same eleven regions of the GREET model (section 2.1) that has been developed at the ZEW Mannheim for the economic part of this research project.

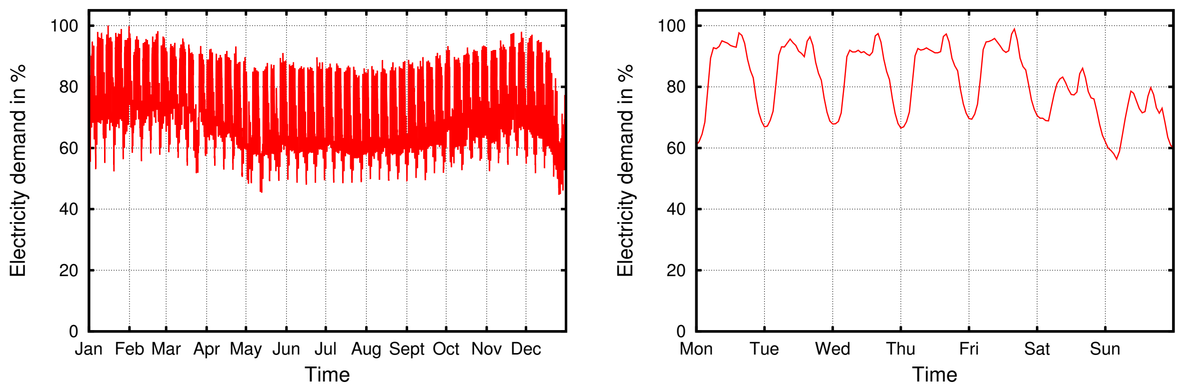
If needed, the user can also define an individual rectangular region for the MEET model by simply using the 'run-file.txt'. There, the geographical position and the size of the rectangular box region can be defined. In this case the whole globe is seen as potential land, and oceans are nor-existent, so that the region can even be placed at coordinates in an ocean.

Because all lines of longitude converge at the geographical poles, the area of a 2.5° grid cell is dependent on its latitude. The area of each trapezium is calculated to give the information of how many power plants are allowed on the area of each grid cell by the MEET model.

The time zone of the regions in the MEET model is dependent on the mean longitude of each region. This mean latitude divided by 15° gives the difference in hours from the UTC time and is needed to adapt the electricity demand curve to each individual region.

3.3. Electricity demand of the model regions

The chronological sequence of the electricity demand side in the MEET model is based on data provided by ENTSO-E[1] for Germany's electricity demand in 2008 with an one hour time resolution (ENTSO-E, 2014). This demand curve includes the typical structures of the seasonal variation, the five working days and the week end, as well as by the general daily behaviour of electricity demand with up to 40 % less during the night as during the daytime (ENTSO-E, 2014) (fig.: 3.3 (a) and (b)). There is more need for electricity in the cold and dark winter season than in the summer, a reduced demand at the weekend due to less consumption by industry and, during any one day, most electricity is needed in daytime with a little reduction during the lunch break and the maximum typically in the afternoon with a strong reduction during the night. This demand curve is scaled by the MEET model with the individual annual sum of electricity demand for each model region given in tab.: 3.3 or by the demand specified by the user, to end up with the hourly individual electricity demand of each model region. The data of the annual sum of electricity demand of the model regions has been taken from the Statistical Review of World Energy by BP (2009) for the year 2008.



(a) (b)

Figure 3.3.: (a) The chronological sequence of electricity demand of the MEET model regions for one year in per cent of the maximum. (b) The chronological sequence of electricity demand of the MEET model regions for one week in per cent of the maximum.

To fit the chronological sequence of the electricity demand to the weather data, the demand curve is adapted by the MEET model to the timezones of the model regions. A differentiation of the electricity demand curve for the northern and southern hemisphere is done by the MEET model to match the seasonal weather with the appropriated electricity demand.

For the case the user of the MEET model defines a region on his own by using the 'run_file.txt' (see section 3.19 and appendix B.1), the annual electricity demand will be adjust to the same ratio of area to

[1] https://www.entsoe.eu

Table 3.3.: Annual electricity demand of the model regions of the MEET model (BP, 2009).

Model region	Region no.	Annual electricity demand [TWh / a]
Asia	(1)	9053
North America	(2)	5172
Europe	(3)	3956
Africa	(4)	638
South America	(5)	1050
New Zealand	(6)	44
Australia	(7)	272

electricity demand, as it is at the model region of Europe. This means about 0.4 GWh per km^2 for the customized model region as standard value.

3.4. Onshore wind power simulation

The simulation of electricity generation by onshore wind power at the MEET model is based on the Modern Era Retrospective analysis for Research and Applications (MERRA) data from the NASA (Lucchesi, 2012) (see also section 3.19) and a representative power curve of a wind turbine. From MERRA the u- and v-component, which means the northward and eastward components, of the wind speed at 10 m above the ground is used to calculate the wind speed by simple trigonometry $v_r = \sqrt{u^2 + v^2}$ in m/s. The air density ρ in kg/m^3 and the roughness length z_0 in m is used for the calculation of the wind power as well. If the data of the air density is not available, data of the air pressure and temperature can also be used to calculate the air density. Therefore the equation of ideal gases

$$\rho = \frac{p}{R_s \cdot T}$$

is used under the assumption of dry air by using the specific gas constant for dry air R_s=287 J/(kg K), the air temperature T in K and the air pressure p in Pa.

At first the wind speed at the hub height of the wind turbine, which is set to 100 m for the onshore wind power at the MEET-model, is calculated by using the logarithmic wind law

$$v_z = v_r \cdot \frac{ln\,(z/z_0)}{ln\,(z_r/z_0)} \qquad [3.1]$$

with z_0 in m as roughness length of the ground, z_r the reference height in this case at 10 m and v_r in m/s the wind speed at the reference height. If there is no data for z_0 available, MEET uses for onshore z_0=0.03 m as standard value, which is in the range of a cultivated landscape with just a few trees or buildings (Stull, 2000) and should represent a typical surrounding for wind turbines. In fact, eq. [3.1] is defined for a neutral atmospheric layering and the lower part of the atmospheric boundary layer up to ca. 50 m to 150 m, which is known as the Prandtl layer (Pichler, 1997). At the moment most hub heights of wind turbines are in the range of the Prandtl layer (compare ENERCON (2013)), but of course, in most cases the atmospheric layering is not neutral. Therefore the logarithmic wind profile (eq. [3.1]) should be adjusted for stable or unstable conditions by an additional function $\Phi_M\left(\frac{z}{L_*}\right)$ based on Monin and Oboukhov (1954). Nevertheless the logarithmic wind profile is a good and very often used approach to determine the wind profile in the boundary layer and can be used at the MEET model.

Since the kinetic energy of the wind hitting orthogonally a surface A in m^2 depends on the air density in the way of

$$E_{kin} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \qquad [3.2]$$

and the power curves of wind turbines are given for a specified reference air density of ρ_{ref}=1.225 kg/m^3, the power curve or the entering wind speed has to be scaled to correct the influence of an air density which differs from ρ_{ref}. So MEET scales the calculated wind speed at hub height in the way it is typically done for modern pitch regulated[2] wind turbines. This is based on setting the kinetic energy of the wind eq.: [3.2] with its actual wind speed v_{site} and air density ρ_{site} equal the kinetic energy of a fictional new wind speed v_{scaled} that allows the use of the reference air density ρ_{ref}:

$$\frac{1}{2} \cdot \rho_{site} \cdot A \cdot v_{site}^3 = \frac{1}{2} \cdot \rho_{ref} \cdot A \cdot v_{scaled}^3. \qquad [3.3]$$

Solve eq.: [3.3] for the new wind speed v_{scaled}, corresponding to the standard air density, results in the desired dependency for the correction:

$$v_{scaled} = v_{site} \cdot \left(\frac{\rho_{site}}{\rho_{ref}}\right)^{1/3}. \qquad [3.4]$$

At the IEC[3] 61400-12 the relationship is used to scale the power curve of a wind turbine for different air densities (Svenningsen, 2010). In the MEET model eq.: [3.4] is used to scale the wind speed that goes to the power curve (fig.: 3.4) given for the standard air density. Both ways of adjustments lead to the same corrected power output at the end.

For the onshore wind power calculation, the MEET model uses the power curve of the Nordex N90 HS wind turbine (fig.: 3.4) to translate the calculated wind speed into a power output for each hour of a year. In principle the power curve used by the MEET-model can be changed easily, but the N90 represents an all-round wind turbine that can be found all over the world (Nordex, 2010) (see also section 3.19 and fig.: 3.13).

In order to represent the park effect[4] (for used distance between wind turbines see section 3.13) and other additional power losses, each calculated power output of onshore wind turbines is scaled by a factor

[2] The ability of wind turbines to rotate their rotor blades around the blade axis for changing their aerodynamics to adapt to different wind conditions typically above the rated power.

[3] International Electrotechnical Commission

[4] Wind shading of a wind turbine due to other wind turbines leading to a lower park efficiency than a single wind turbine would achieve.

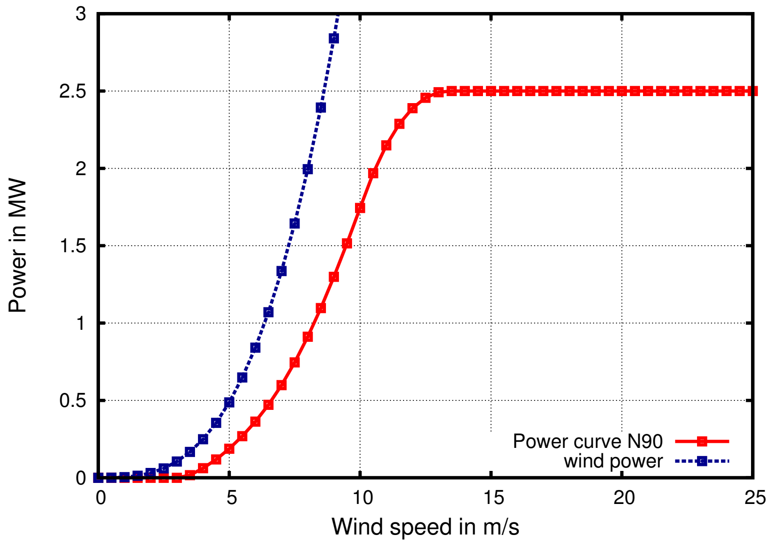


Figure 3.4.: Power curve of Nordex N90 2.5 MW (Nordex, 2010) and wind power passing the rotor disc area of 6362 m^2.

of 0.78 at the MEET model. So the calculated wind power gets closer to real feed-in data based on the EEG[5] (see chap. 4.2.3).

3.5. Offshore wind power simulation

The generation of electricity by offshore wind power in the MEET model is calculated in much the same way it is done for onshore (see section 3.4). As the wind speed increases stronger with the height offshore due to the lower roughness of the sea, the hub height for which the wind speed is calculated is only 90 m. The roughness length z_0 is given as well by MERRA data.

Because the progress of the establishment of large offshore wind parks is not that good and time series for the power generation by such wind parks has been absent for this work, there is no additional scaling of the calculated electricity generation for offshore wind turbines in the MEET model. Offshore wind power turbines are specifically designed with a higher rated power than typical onshore units to compensate for the higher costs of installation, together with maintenance costs, but enabling better wind conditions to be used. Therefore at the MEET-model the power curve of the REpower 5M (Staffell, 2012) is used (fig.: 3.5). Not only the rated power of 5 MW is twice that of the onshore Nordex N90 HS, but also the cut out wind speed[6] is at a higher value of 30 m/s.

[5]Erneuerbare-Energien-Gesetz; German Renewable Energy Law.

[6]This is the maximum wind speed a wind turbine is designed to generate electricity before it needs to turn its rotor blades out of the wind to avoid damaging the construction.

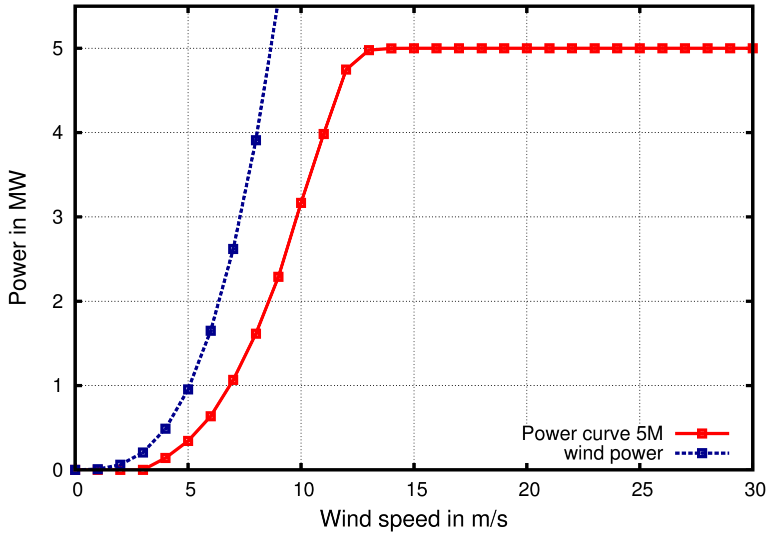


Figure 3.5.: Power curve of REpower 5M (Staffell, 2012) and wind power passing the rotor disc area of 12469 m^2.

3.6. Wave power converter simulation

Wave power converters are represented in the MEET model by the WD 7MW Wave Dragon module (Tedd, 2007) with 7 MW rated power. Wave Dragon is a floating platform that is flooded by collected waves and uses the runoff water for the turbines.

To calculate the electric power generated by wave power converters, the MEET model uses ERA-Interim data (Janssen et al., 1997) of the European Centre for Medium-Range Weather Forcast (ECMWF) for the ocean wave height and the period of this waves (see also section 3.19). Similar to the power curves of wind turbines, a power matrix of the wave power converter module is given to the MEET model.

The resulting power for the wave heights and periods the Wave Dragon module is designed for are given by the power matrix[7] (tab.: 3.4) of the WD 7MW module. The tabular 3.4 has some skipped power values, because these combinations of wave heights and periods are not possible due to the breaking of waves. If required this power matrix can be adjusted by the user for a different wave power converter module. For further information on Wave Dragon see also http:\\www.wavedragon.net and Tedd (2007).

[7] The power matrix for WD 7MW of 2008 was given by personal communication with Wave Dragon ApS, Denmark

Table 3.4.: Power matrix of the Wave Dragon 7 MW module with values given in kW.

Wave hight in m \ Period in s	5	6	7	8	9	10	11	12	13	14	15	16	17
1	160	250	360	360	360	360	360	360	320	280	250	220	180
1.5	360	420	540	740	740	740	740	740	660	590	520	440	370
2	640	700	840	900	1190	1190	1190	1190	1070	950	830	710	590
2.5	1170	1260	1330	1400	1580	2040	2040	2040	1830	1630	1430	1220	1020
3		1450	1610	1750	2000	2620	2620	2620	2360	2100	1840	1570	1310
3.5			2420	2660	2940	3220	4100	4100	3690	3280	2870	2460	2050
4			2840	3220	3710	4200	5320	5320	4430	3930	3440	2950	2460
4.5				3920	4550	5180	6650	6720	5600	4970	4030	3450	2880
5				4610	5320	6020	7000	7000	6790	6090	5250	3950	3300
5.5					5740	7000	7000	7000	7000	7000	6090	4320	3600
6					6720	7000	7000	7000	7000	7000	6860	5110	4200
6.5						7000	7000	7000	7000	7000	7000	5950	4970
7						7000	7000	7000	7000	7000	7000	6650	5740

3.7. Photovoltaic power simulation

For the calculation of the electricity production by photovoltaics, the MEET model uses MERRA data of global solar radiation on an horizontal plane at ground level, solar radiation at the top of the atmosphere, wind speed at 10 m above the ground and air temperature at 2 m above the ground. In a first step the fraction of the direct and the diffuse part of global solar radiation is calculated for the simulation of the photovoltaics as well as the CSP (section 3.8). The fraction of the diffuse to the global radiation at the ground

$$d_{dif} = \frac{I_{diffuse}}{I_{global}} \qquad [3.5]$$

is calculated by using the BRL model of Boland, Ridley and Lauret (Ridley et al., 2009) and the fraction of direct radiation results simply $d_{dir} = 1 - d_{dif}$. The BRL model is based on multiple predictors tested on their relevance to identify the fraction of diffuse solar radiation on different sites of the world. The parameters are the result of a minimum least squares for the data. It delivers, in comparison to other models, good results for locations on the northern as well as on the southern hemisphere and can be used as an universal model (Ridley et al., 2009), which is important for the global acting MEET model.

As d_{dif} results in the BRL model from multiple predictors, the hourly clearness index

$$k_t = \frac{I_{global}}{I_0} \qquad [3.6]$$

is needed, with I_0 as the extraterrestrial irradiation at the top of the atmosphere and I_{global} as the irradiation on the ground. The daily clearness index K_t is also needed and can be calculated by the sum of the hourly values per day as

$$K_t = \frac{\sum_{j=1}^{24} I_{global_j}}{\sum_{j=1}^{24} I_{0_j}}. \qquad [3.7]$$

The Apparent Solar Time[8] AST is considered for d_{dif} as well as the solar elevation angle[9] α_s in degree (for calculation of AST and α_s see appendix A). Finally, a persistence factor is defined for $t \in [0, 23]$ as:

$$\psi = \begin{cases} \frac{k_{t-1}+k_{t+1}}{2} & \text{for sunrise} < t < \text{sunset} \\ k_{t+1} & \text{for } t = \text{sunrise} \\ k_{t-1} & \text{for } t = \text{sunset} \end{cases} \qquad [3.8]$$

Once all the values of the equations 3.6 - 3.8, the AST and α_s are calculated, the fraction of diffuse solar radiation is given by:

$$d_{dif} = \frac{1}{1 + e^{-5.38+6.63 \cdot k_t + 0.006 \cdot AST - 0.007 \cdot \alpha_s + 1.75 \cdot K_t + 1.31 \cdot \psi}} \qquad [3.9]$$

For a clear sky d_{dif} goes down to values of about 0.1 and for clouds up to almost 1. An example of the calculated diffuse fraction of solar radiation based on MERRA data is given by (fig.: 3.6) as daily average values for 2009 and hourly values for one week at the location 50° N and 7.5° E in Germany and 37.5° N and 3° W in Spain. As expected decreases the fraction of diffuse solar radiation during noon and in the summer season, having less clouds and a larger solar elevation angle.

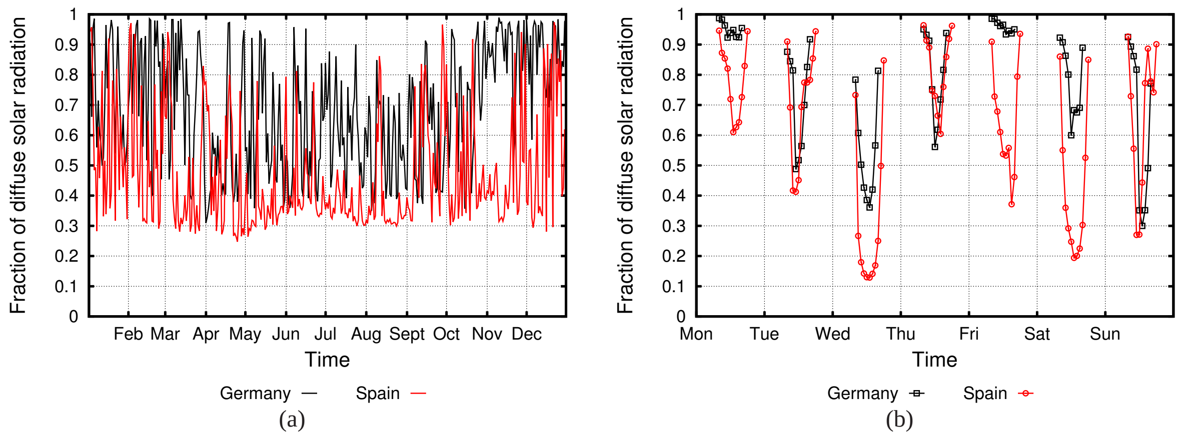


Figure 3.6.: Fraction of diffuse solar radiation d_{dif} calculated by the BRL model of Ridley et al. (2009). (a) Daily average values for 2009. (b) Hourly values for the week from 19th to 25th January 2009.

Since the global solar radiation data from MERRA is for a horizontal plane and the photovoltaic modules are assumed to face south in the northern hemisphere (or north in the southern hemisphere)

[8]The true time at a place depending on the sun.
[9]The elevation of the sun against the horizon.

with an angle of 30° to the horizontal plane, a correction of the direct part of the solar radiation is given by

$$I_{dir\_corrected} = I_{global} \cdot d_{dir} \cdot \text{zenit\_correction} \cdot \text{azimut\_correction} \quad [3.10]$$

with

$$\begin{aligned} d_{dir} &= 1 - d_{dif}, & [3.11] \\ \text{zenit\_correction} &= \frac{cos(60-\alpha_s)}{cos(90-\alpha_s)}, & [3.12] \\ \text{azimut\_correction} &= |cos(180-\alpha_a)|, & [3.13] \end{aligned}$$

and α_a as the azimuth angle of the position of the sun. The solar angle α_s and the azimuth angle of the sun α_a are calculated by using the algorithm of DIN[10] 5034 as described in Quaschning (2009) and Nunnenmann (2011) (for details see appendix: A).

The efficiency of a PV-module to convert the incoming solar radiation into electricity $\eta_{PV} = 0.14$ is assumed, as it is in the medium range of standard polycrystalline PV-modules, for example, of SCHOTT solar (2011).

To take care of the power degression of the PV-modules due to ageing, a loss of 0.7 % of the initial PV-module efficiency per year (SCHOTT solar, 2011) has been used. This leads for the assumption of an averaged PV-module age of 10 years to an additional efficiency reduction of about 7 %. Thus the age loss factor $\eta_{pv\_age} = 0.93$ is defined for the MEET model to adjust the PV-module efficiency.

Under low radiation conditions, which means less than 200 W/m^2 on the PV-module, an additional reduction of the power output is taken into account. Regarding the technical specifications of SCHOTT solar (2011) the PV-module efficiency reaches only 97 % of η_{PV}.

To consider the effect of efficiency reduction due to increasing PV-module temperature, its temperature is calculated by using the model of Govindasamy et al. (2003). There the ambient air temperature $T_{ambient}$ in °C, the solar radiation on the PV-module I in W/m^2 and the wind speed v in m/s have been identified as the main driving variables for the temperature of a PV-module T_{module} in °C. Using measured data and a neuronal network, they ended with a simple linear relationship for the temperature of a PV-module and its ambient conditions in the way as follows:

$$T_{module} = 0.943 \cdot T_{ambient} + 0.028 \cdot I - 1.528 \cdot v + 4.3. \quad [3.14]$$

Of course eq. [3.14] has been evaluated only for one module type, but its results correlated with the measured temperature with an R^2 of 0.95 to 0.96 (Govindasamy et al., 2003) quite well and works for the calculations of the MEET model.

The efficiency reduction of PV modules due to an increasing temperature is typically given as 0.5 % per °C deviation from the 25 °C standard (Brinkworth and Sandberg, 2006). Becauce PV modules can

[10]German industry for standards; Deutsches Institut für Normung

reach up to 70 °C (Notton et al., 2005), the effect of the module temperature should not be ignored and so the correction factor $\eta_{T-corect}$ for the PV power output is calculated for the MEET model by

$$\eta_{T-corect} = 0.995^{\Delta T_{pv25}} \quad [3.15]$$

with $\Delta T_{pv25} = 25\,°C - T_{module}$ as the difference of the module temperature to the standard temperature.

At the end additional system losses such as the inverter, etc. are assumed to be 22 %, so that the system efficency factor $\eta_{pv\_sys} = 0.78$ is used to reach an even more realistic electricity output by the pv modules. This value is also close to the losses calculated by the Photovoltaic Geographical Information System (PVGIS)[11]. Consider now eq. [3.6] to [3.15] and the described assumptions, the electricity output by pv modules in the MEET model results in:

$$P_{pv} = \left(I_{global} \cdot d_{dif} + I_{dir\_corrected}\right) \cdot \eta_{pv} \cdot \eta_{pv\_age} \cdot \eta_{T-corect} \cdot \eta_{pv\_sys}. \quad [3.16]$$

3.8. Concentrating Solar Power simulation

The simulation routine for Concentrating Solar Power (CSP) plants of the MEET model was developed by Elena Nunnenmann during her bachelor thesis (Nunnenmann, 2011). It considers the so called parabolic trough solar thermal power plants. These CSP plants have already been built, for example, in Spain and are known under the name Andasol.

For the simulation, MERRA data of the global solar radiation on a horizontal plain at the ground and the solar radiation at the top of the atmosphere is used. In addition, the rated power (47.539 MW) of the CSP, the maximum heat power of the collector field (145.570 MW_{therm}), and the heat energy storage capacity (1010 MWh_{therm}) are needed (Nunnenmann, 2011). It is given to the MEET model by an additional file that can be easily adapted and the values are orientated on the Andasol power plants in Spain (Solar Millennium AG, 2008).

The parabolic trough CSP uses a mirror in the shape of an parabolic trough, that concentrates the sunlight on to a receiver tube in the focus line of the trough. To generate enough heat to run the power plant, many of the mirror troughs are placed side by side with typically a North-South orientation. The troughs are able to follow the sun in an East-West direction by rotating along their axes.

To calculate the heat that is gained by the solar field of the CSP, the direct solar radiation hitting the troughs is needed. This is due to the fact that only direct solar radiation can be concentrated and so the global radiation data needs to be separated into its direct and diffuse part. This is done in the same way as for the simulation of the photovoltaics in section 3.7 by using the BRL model of Boland, Ridley and Lauret (Ridley et al., 2009) with eq. [3.9]. The position of the sun is needed as well, because the solar radiation data is given for a horizontal plane and the mirror troughs are able to follow the sun along one axis. For very low elevations of the sun, shading of the troughs by their adjacent ones reduces the usable solar radiation. An analogy of the simulation of the photovoltaic in section 3.7 the solar angle α_s

[11] http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php

and the azimuth angle α_a of the sun are calculated by using the algorithm of DIN 5034 as described in the appendix A. Considering optical losses, the incident angle of the sun relative to the normal of the parabolic trough and the absorber efficiency, the thermal power which the solar field of an CSP in the MEET model can provide is given by:

$$P_{CSP\_therm} = \frac{I_{global} \cdot \left(1 - d_{dif}\right)}{cos\left(\beta\right)} \cdot A_{CSP} \cdot \left(1 - \eta_{shadow}\right) \cdot \eta_{opt} \cdot \eta_{iam} \qquad [3.17]$$

I_{global} is the solar radiation in W/m^2 for a horizontal plane, that is reduced to its direct radiation part by multiplying one minus the diffuse fraction d_{dif} and corrected for the plane of the trough by $cos(\beta)$. The tracing angle of the trough β goes from East (β = 90°) to West (β = -90°) and can be calculated from the solar position as

$$\beta = arctan\left(\frac{sin(\alpha_a)}{tan(\alpha_s)}\right). \qquad [3.18]$$

The total area of the solar field A_{CSP} = 526417 m^2 is needed for eq.: [3.17] as well as the losses by shading of the troughs at low positions of the sun. The shading factor is given as

$$\eta_{shadow} = \frac{(n_{row} - 1) \cdot (d_{row} - d_s \cdot cos(\beta))}{n_{row} \cdot d_{row}} \qquad [3.19]$$

with n_{row} the number of rows of parabolic troughs at the solar collector field, d_{row} = 5.76 m as the aperture of a parabolic trough and d_s = 17.3 m as the distance between two rows of troughs.

Finally eq.: [3.17] requires the optical efficiency η_{opt} = 0.71 and the incidence angle modifier η_{iam}. The optical efficiency considers the reflectivity of the mirror, the transmission of the glass tube around the absorber tube and the absorptivity of the absorber itself (Montes et al., 2009). The incidence angle modifier η_{iam} respects the effect of a changing focus of the parabolic trough for sunlight that is not incoming orthogonal to the trough and is defined in Montes et al. (2009) for the Eurotrough-Collector as

$$\eta_{iam} = 1 - 2.859621 \cdot 10^{-5} \cdot \frac{\Theta^2}{cos(\Theta)} - 5.25097 \cdot 10^{-4} \cdot \frac{\Theta}{cos(\Theta)}. \qquad [3.20]$$

While the incidence angle of the sunlight to the trough is given as

$$\Theta = acos\left(\sqrt{1 - cos^2\left(\alpha_s\right) \cdot cos^2\left(\alpha_a\right)}\right). \qquad [3.21]$$

Once the collected solar radiation was used to heat up the thermal fluid that is pumped through the absorber tubes of the CSP, thermal losses occur on its way through the absorber tube and to the power plant. Since the length of the way depends on the number of rows of collectors, the losses need to be a function of this number. Based on simulations of those heat losses for the Eurotrough-Collector by Montes et al. (2009), the heat losses can be described as (Nunnenmann, 2011)

$$P_{therm\_loss} = \left(-221000 + 186340 \cdot \frac{n_{row}}{2}\right). \qquad [3.22]$$

After these losses have been subtracted from the collected heat described by eq. [3.17], the remaining heat power can be used directly to provide the thermal power plant or it can be stored in a heat storage tank with a capacity of 1010 MWh_{therm} (Nunnenmann, 2011). This heat storage makes the CSP much more flexible and it can supply the power plant for up to 6.9 full load hours. For the heat storage, an averaged heat loss of 0.05 % per hour has been assumed.

Typically, a CSP plant being equipped with a heat storage has a larger solar field compared to its generator power than other CSP plants. This is required to allow to fill the heat storage not even in times when less electricity is needed than the thermal power plant actually could generate, but also when the thermal power plant is generating electricity at full load. This stored heat can be used if, for example, clouds cover the sun, or at night. In the case of the CSP in the MEET model the solar field has an area of 526,417 m^2, which is almost the same as the existing CSP plant, Andasol, in Spain (Mehos, 2008). For an assumed solar irradiation of 1000 W/m^2 this solar field would provide about 2.5 times the heat that the associated thermal power plant could use. This fraction of the theoretical generated heat power to the usable heat power at the thermal power plant is called the solar multiple ($P_{CSP\_therm}/P_{therm\_max}$) and reaches typically from a value of 1.3 to 3 (IRENA, 2012) while it is 2.5 for the CSP of the MEET model.

The thermal power plant itself uses the heat to generate electricity with varying efficiency, depending on its load defined as P_{therm}/P_{therm_max}. The optimal efficiency is reached at full load with η_{therm_CSP} = 0.3765. For reduced loads, the efficiency of the thermal power plant of the CSP is calculated in the MEET model by

$$\eta_{therm\_CSP} = 0.3967 - 0.2171 \cdot 0.093^{(P_{therm}/P_{therm\_max})}. \qquad [3.23]$$

This equation is the result of a fit based on data of Montes et al. (2009). To avoid wasting thermal power by running the thermal power plant at low loads, the heat will be given to the heat storage instead to the power plant once η_{therm_CSP} goes below 0.3. Or, if electricity is needed and the heat storage contains existing heat, it is used to bring the load of the thermal power plant high enough to raise its efficiency above the limit of 0.3.

Finally it needs to be considered, that a CSP plant does not only generate electricity, it also needs it for pumping the thermal fluid through the pipes of the solar field and other consumers. These so called parasitic losses (η_{para_CSP}) use 13 % of electricity output of the CSP plant (Kutscher et al., 2010). Using eq.: [3.17] and eq.: [3.8], the final electricity output can be defined as

$$\mathrm{P}_{CSP} = P_{CSP\_therm} \cdot \eta_{therm\_CSP} \cdot (1 - \eta_{para\_CSP}). \qquad [3.24]$$

A more detailed description of the simulation of this power plant type can be found at Nunnenmann (2011) and Quaschning (2009).

3.9. Runoff hydro power simulation

The use of hydro power for electricity generation for the simulation in the MEET model is reduced to river runoff hydro power. To allow shipping traffic and avoid flooding the power output of the runoff hydro power plants is assumed to be not regulable and with a constant electricity generation. It only follows the seasonal variation of the rivers water flow rate with an idealized annual cycle represented by a cosine. The amplitude of the seasonal variety has been assumed to 30 % for the MEET model, so that the hourly power output of runoff hydro power plants is defined as:

$$P_{hydro}(t) = P_0 + P_0 \cdot 0.3 \cdot \cos\left(\frac{2 \cdot \pi \cdot t}{8760\,h + \varphi}\right) \quad [3.25]$$

with P_0 as standard power output of the hydro power and t the hour of the year. To shift the maximum of the electricity generation by hydro power into the Spring season, when the combination of rain and melting water let the stream grow to their maximum, φ of eq. [3.25] is given as:

$$\begin{aligned} \varphi &= -\frac{1}{2} \cdot \pi \qquad \text{(northern hemisphere)} \\ \varphi &= -\frac{3}{2} \cdot \pi \qquad \text{(southern hemisphere)}. \end{aligned}$$

Additionally the power output is scaled in a way that the degree of capacity utilization over one year ends with 30 % as it is the case for Europe in Nitsch et al. (2010a) and Teske et al. (2010).

3.10. Bio-fuel power plant simulation

The simulation of the electricity generation by bio-fuel fired power plants is treated very poorly in the MEET model. The idea is that power plants that use bio-fuels can be used in the way gas, coal and nuclear power plants are used, but its CO_2 balance is ideally zero due to the bio-fuel. Because of its renewable fuel, bio-fuel power plants have a priority for generating electricity against gas, coal and nuclear power plants in the MEET model. But bio-fuel is still a limited energy source that needs to be bought, so bio-power plants will only be used as balancing energy.

Table 3.5.: Maximum electricity that could be generated by bio-fuel power per year in the MEET model based on Teske et al. (2010).

Region	Electricity limit of bio-fuel power [TWh / a]
Asia	405
North America	245
Europe	137
Africa	78
South America	239
New Zealand	nan.
Australia	58

Since bio-power plants are treated as relatively small units with a rated power between 1 MW and 25 MW (Trieb et al., 2009), the assumed 20 MW rated power per plant for the bio-power plants of the

MEET model do not require to consider the ramp-up and -down time as the model time-step is at least one hour. There is also no differentiation between biomass, biogas or liquids. The maximum amount of producible electricity by bio-fuel power plants can be defined in the 'run-file.txt' in terms of kWh per year for each region of the MEET model. As default limits, the maximum amount of electricity generated by biomass given in the energy [r]evolution study (Teske et al., 2010) is used (see tab. 3.5), but if needed for a special scenario, it can be easily adjusted.

3.11. Simulation of gas, coal and nuclear power plants

Since gas, coal and nuclear power plants use a fuel to generate electricity, there is no dependency on the weather conditions. But because their fuels are limited resources and cause variable costs while using these plants, renewable energies in the MEET model have a priority in feed-in the electricity generated.

The gas, coal and nuclear power plants of the MEET model differ in the rated power per plant unit. The downtime, the minimum load they are able to run and the averaged emissions of CO_2 per kWh of generated electricity (see tab. 3.6). Once a thermal power plant is switched off, it takes time to stop all processes and it needs to cool down slowly to reduce thermal stresses of the materials. The time taken until the power plant is able to generate electricity again, is called the downtime and depends on the plant type. For the MEET model the time ranges given in Weindorf (2011) have been averaged for each plant type. The values of the minimum load at which a power plant type is able to generate electricity results as an average from the values given in Weindorf (2011). The CO_2 emissions of coal with 0.95 g/kWh and gas with 0.45 g/kWh as averaged values per generated kWh of electricity for the MEET model are taken from the data-Excel file of the TRANS-CSP study (Trieb, 2006).

Table 3.6.: Behaviour of gas, coal and nuclear power plants in the MEET model.

Type	Rated power [MW]	Min. load [%]	Downtime [h]	CO_2 emissions [kg / kWh]
Nuclear power plant	1000	50	55	-
Coal power plant	500	39	14	0.95
Gas power plant	340	18	3	0.45

Once the gas, coal and nuclear power plants are required to feed in electricity, the MEET model provides a priority of use, starting with nuclear power plants before coal power plants and ending with gas power plants. This sequence results in the flexibility of the power plants which typically fit well to the economic view of lowest variable costs resulting in the merit order.

3.12. Ranking of sites for electricity production

The potentials of using renewable energy to generate electricity are highly dependent on the geographical position of the power plant and vary from year to year (compare fig.: 4.1 to 4.5 of section 4.1). To decide where the MEET model starts to install the power plants using these renewable energies, a ranking is needed to ensure that the best sites are used first.

The ranking of the model grid cells is based on the potential electricity output per peak power in terms of full load hours of the plants. Starting with the grid cell having the highest potential in terms of the most full load hours, the MEET model generates a list of the potentials of each grid cell for the model regions. The base of this ranking is given by the calculation described in section 3.4 to 3.8.

To considerer the annual variations of electricity generation by weather dependent power plants, the potentials have been calculated by the MEET model for all eleven years of weather data from 2000 to 2010 and then averaged. These resulting maps of the potentials of power plants, using renewable energies and their standard deviation as well, is discussed in section 4.1 and can be found in the above mentioned figures.

Indeed the electricity generation potential is not the only criteria for the placement of a power plant using renewable energy, but since the MEET model consider no losses due to an electricity grid and has no information about restricted areas, the electricity generation potential of a grid cell is the only criteria for the ranking. Regarding the size of a grid cell with its 2.5° by 2.5° and the allowed share for the installation of power plants of only a view percentage of the grid cell area, the ability to find a favourable location for the power plants in the grid cell is quite good.

3.13. Installation of renewable energy power plants in the MEET model regions

To provide the electricity demand, the MEET model adds power plants to the model regions considering the defined power mix of the scenario. The total required capacity of power plants to suit electricity supply and demand is calculated by the MEET model as described in section 3.17. The rules of how the MEET model manage the placement of the power plants is described in the following.

Only power plants that are dependent on the weather and the distribution of this renewable energies have a defined placement to grid cells of a model region. Because there is no electricity grid and the generated electricity is defined as available anywhere in a model region, the position of power plants being independent of the weather is not of a real importance. So the MEET model calculates only the amount of needed gas, coal, nuclear, runoff hydro, and bio power plants and not their location.

If a simulation requires additional power from a specific power plant smaller than the rated power of the plant type, a complete power plant is added, even if this alters the mix of power plants slightly from the one defined by the user. The smallest units of adding electricity generation capacities are 1000 MW of nuclear power, 500 MW of coal power, 340 MW of gas power and 20 MW of bio power. River runoff power is allowed to be added in steps of 1 kW.

The smallest units of adding power plants having weather dependent electricity generation are 2.5 MW of onshore wind power, 5 MW of offshore wind power, 7 MW of wave power, 1 kW of PV power and 47 MW of CSP. Additionally, the placing of the weather dependent power plants is related to grid cells. For the order of using the grid cells in terms of site the power plants, the ranking described in section 3.12 is used. Based on the ranking, the MEET model installs the power plants required for the electricity supply scenario, starting with the best grid cell (most full load hours) first. Once the maximum allowed area of the grid cell is used, MEET starts to install further power plant capacities to the second best grid cell and so on, until all required power plants are sited. In this way the potential full load hours of the power plants being installed decreases with each additional required grid cell that is used by the MEET model for the electricity supply of a model region as given in fig.: 3.7 to fig.: 3.11. The potentials reach from grid cells with very poor conditions of just 500 full load hours up to the best sites for CSP and offshore wind power with 6500 full load hours.

Looking at the electricity generation potentials of using wind, wave or solar power (compare fig.: 4.1 to fig.: 4.5 of section 4.1) and the area such an energy converter requires, a quite small power density in the range of 1 W/m^2 to 20 W/m^2 is the result. So, compared to power plants fired by an energy carrier such as coal that can be transported to any place and even has a high energy density, the power plants using wind, waves or sun have a significant need of space. To ensure that they will not dominate or even overcompensate the area of a grid cell of the model regions, the MEET model has to consider limits of land use while placing the needed capacity of wind, wave and solar power using power plants.

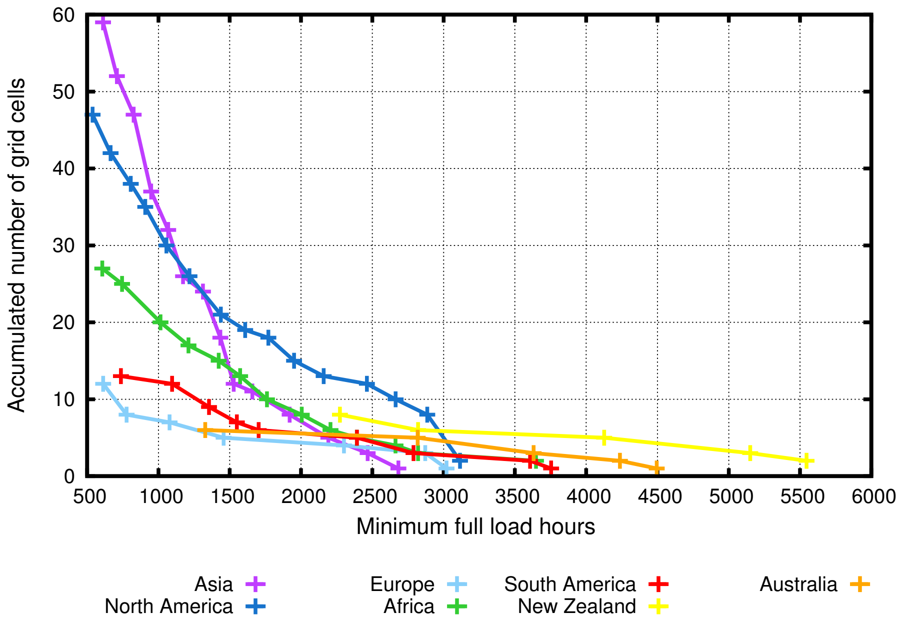


Figure 3.7.: Potential full load hours of wave energy as function of the utilised grid cells of the model regions.

The required area of an onshore wind turbine for the MEET model is set to 5d times 5d which means five times the turbine rotor diameter squared, which is rather larger then the 4d spacing used for the study

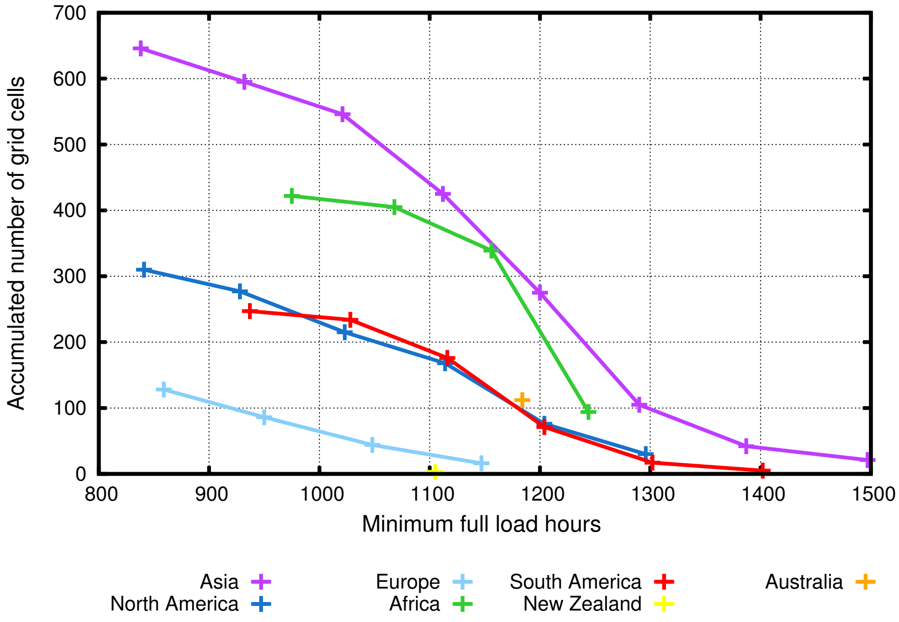


Figure 3.8.: Potential full load hours of PV energy as function of the utilised grid cells of the model regions.

on the wind potential of Germany by Bofinger et al. (2011). The rotor diameter of the standard Nordex N90 wind turbine is 90 m and therefore its needed area results with 0.2 km^2 for the MEET model. As the maximum share of the area of a grid cell for onshore wind power a fraction of 5 % is asumed. This seems to be a quite feasable number as the study of Bofinger et al. (2011) suggeste a potential available area for the use of wind power in Germany with a fraction of 8 %. This potential should be even higher in many other countries since the population density of Germany is quite high.

The offshore wind turbines required area is defined by the same rule of 5d times 5d (Bofinger et al., 2011) as used for the onshore wind turbines. But the rotor diameter of the standard REpower 5M is 126 m. To allow the spreading of wind parks inside a grid cell and reduce the need of placing them too far from the coast, the maximum share offshore wind turbines are allowed to use is set at 2 % of a grid cell. An increased spread of offshore wind parks is desirable, as the wind needs a longer distance to recover its speed after passing through a windpark due to the reduced surface roughness and air mixing compared to onshore conditions.

In the case of wave power converters[12], the limitation of placing them is not based on the area, but on the length of a grid cell. This length is the maximum size of a wave front the farm of wave dragon modules can face in a grid cell. Since the wave dragon modules should not be placed further than 100 km from the coast but still require a minimum water depth of 25 m (WaveDragon, 2003) the space is clearly restricted. To afford a good efficiency by reducing shading effects due to other wave dragon modules, the MEET model places those 300 m wide modules with a spacing of 300 m from its adjacent module as

[12]Wave dragon modules.

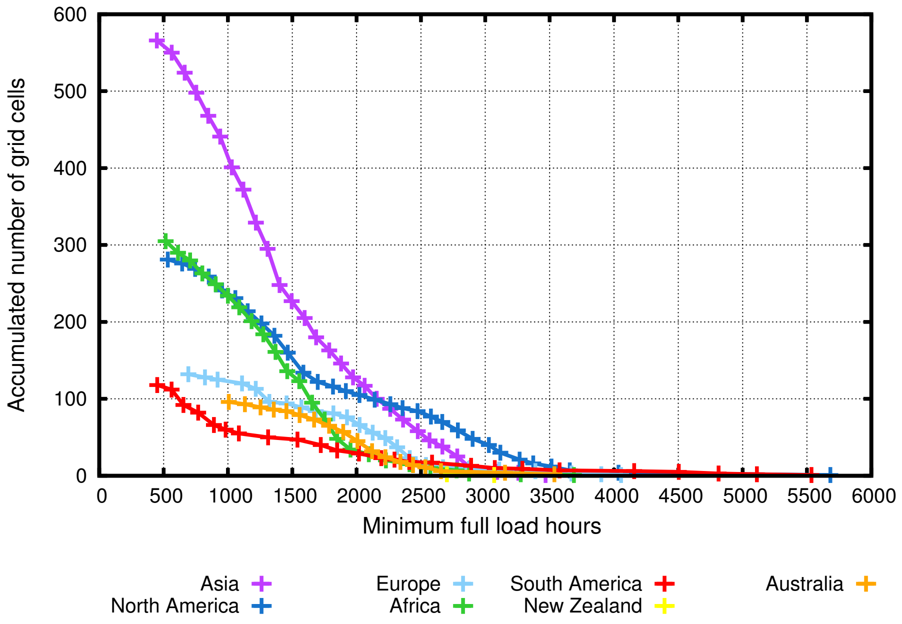


Figure 3.9.: Potential full load hours of onshore wind energy as function of the utilised grid cells of the model regions.

suggested in WaveDragon (2003). In this way, the MEET model is allowed to place up to three staggered lanes of the 7 MW wave dragon modules.

For the placement of PV-modules, and regarding the module efficiency of 0.14, an area of just over 7 m^2 per kW peak is required. The maximum share of PV per grid cell of the MEET model is set to 0.6 %, which easily fits the estimated available PV-area of 0.8 % for Germany (Braun and Oehsen, 2012). Taking this small share into account, the chance to place the PV-cells on a roof top of a building is advantageous so the effective required land is much reduced.

The required area per parabolic concentrating solar power plant of the MEET model is just over 500,000 m^2 (Mehos, 2008). As a share of CSP for a grid cell, 1 % has been assumed for the simulations of the MEET model.

Finally it should be mentioned that often the area used by renewable energy power plants can be used for an other purpose as well. For example, the area of a wind park can still be used for agriculture, wave power converter can be used to protect coastlines and PV-modules placed on a rooftop will not directly effect the available area.

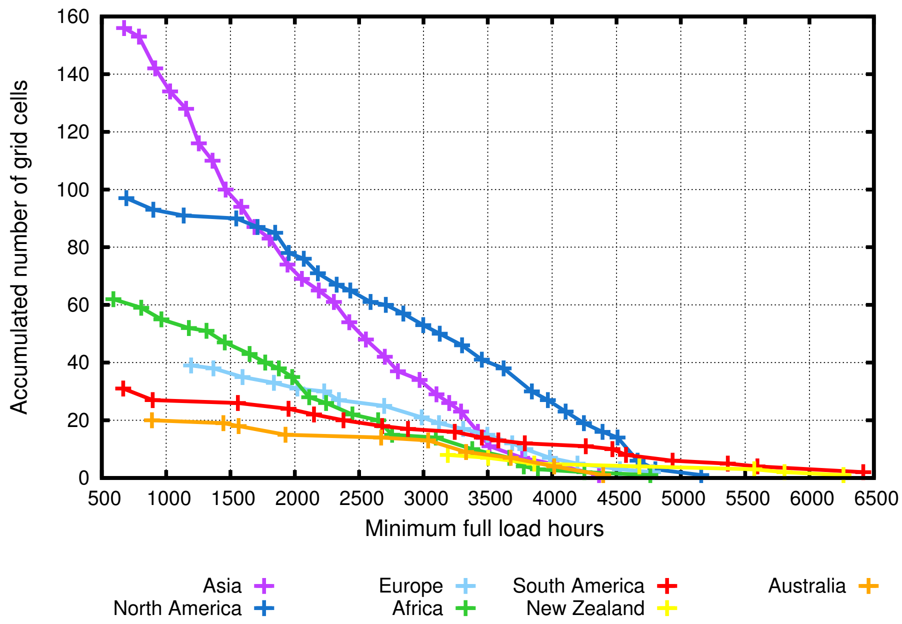


Figure 3.10.: Potential full load hours of offshore wind energy as function of the utilised grid cells of the model regions.

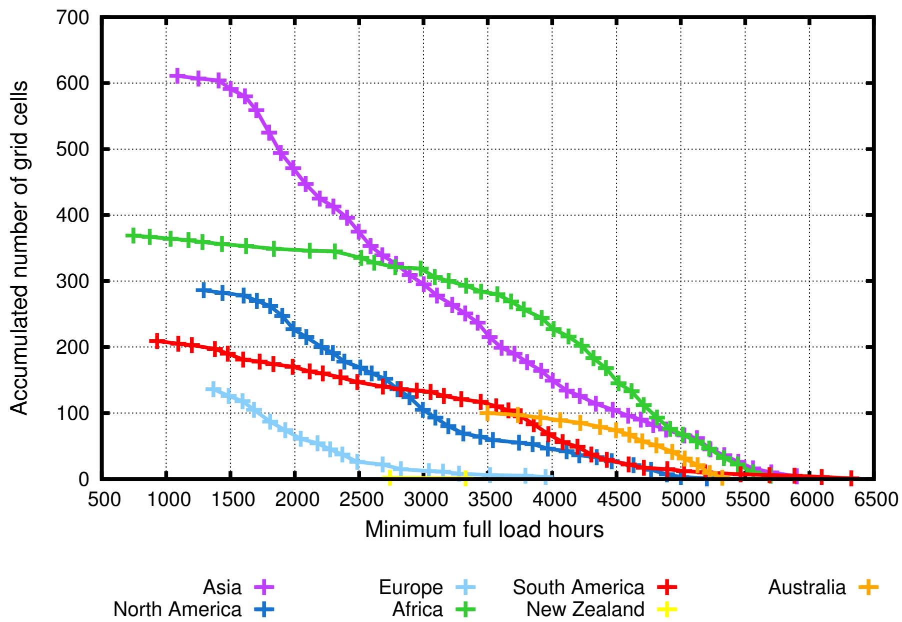


Figure 3.11.: Potential full load hours of CSP energy as function of the utilised grid cells of the model regions.

3.14. Calculate generated electricity by non controllable sources

After the power plants have been sited as described in section 3.13, a time series of electricity production by the plants using non-controllable energy sources is calculated for each model region. Therefore, the electricity generated by on- and offshore wind turbines, wave power converters, PV cells and river runoff water power (as described in section 3.4, 3.5, 3.6, 3.7 and 3.9) of all used model grid cells is summed up for each model time step. This can be done since the assumed perfect electricity grid (section 3.20) allows the MEET model to use this electricity all over the model region.

The resulting time series of hourly available electric energy, together with the demand curve, forms the base for the adaption of loads and the management of controllable power plants in the coming sections 3.15 and 3.16.

3.15. Load management and electro mobility

The MEET models allows the user to create energy supply scenarios by considering the possibility of load management and or electro mobility. Both options can be easily defined in the 'run_file.txt' (appendix B.1).

Load management means that the demand for electricity can be shifted in a certain range of time and quantity to balance the generation and demand of electric power. This is done by delaying a part of the electricity demand for some hours to a time where more electric power will be available as, for example, at midday when solar power reaches its daily maximum. The other way is to bring additional electricity consumption to periods with an excess electric power. This will reduce or even avoid the need for backup power plants or energy storage. The MEET model allows the user to choose the time range the demand can be shifted as a number of time steps which means modeled hours and to decide how much demand in a percentage of the actual demand is allowed to be shifted. Typically, one can imagine, that in a smart electricity grid with intelligent consumers, the electricity demands of washing machines, cooling systems or other flexible processes could be used to shift their load for some hours.

Electro mobility in terms of electric cars also gives the opportunity to shift electric loads for some hours due to their batteries and long parking periods. Thus, the user can set the number of electric cars per model region for the MEET model. The average of daily driven kilometers per car and region has to be defined as well. For example, 50 km would be a good figure as daily driven distance for Germany as 70 % of all user do not drive more than this each day (VDE, 2010). Today, a typical capacity of an electric car or plug-in hybrid batteries is on the order of 15 kWh (Bünger et al., 2009; Böcker et al., 2010), but can be adjusted for the MEET model as well. Finally, it is needed to define the maximum fraction of cars that are in use on the roads at the same time. For Germany this fraction has a daily peak of around 24 %, but most of the time it is much lower (Follmer et al., 2010) which shows that most cars would have the opportunity to be connected to the electricity grid. In principal the batteries of the parked electric cars could be used as energy storage which is known as the vehicle to grid concept, but for the

MEET model the electric cars are seen only as additional electricity consumers with the opportunity to shift this demand during the day.

The additional electricity demand of electric cars is calculated by the MEET model based on the assumption that 0.15 kWh/km would be needed by an electric car (Böcker et al., 2010). Each car has to be charged and used at least once a day, but there is just a small percentage of cars that are in use at the same time and all the other car batteries can be electrical charged over the remainder of the day. A maximum charge power of 3 kW is allowed as it could be managed with a standard power socket.

The decisions of the load management and the charging of electric cars are based on the available electric power by power plants using non controllable energy sources (section 3.14). So this routine of the MEET model considers at each time step the electricity production and demand over the whole range of shiftable loads to identify the best way of using the electricity generated by power plants using non controllable energy sources. This means that shiftable electricity demand and charging of electric cars will be placed in periods when the power plants produce the most electricity compared to the demand. For energy supply scenarios dominated by individual controllable power plants, there is almost no need to shift loads, since the electricity simply can be generated on demand.

3.16. Power supply management

If the electricity production by power plants using non controllable energy sources was calculated for the actual time step (section 3.14) but does not meet the demand even when load management has been done (section 3.15), an additional power supply management is needed. This will use, depending on the defined power supply scenario the CSP, bio, nuclear, coal or gas power plants and finally the energy storage to bring generation and demand of electricity together.

Parabolic CSP plants as implemented in the MEET model (section 3.8) make use of a thermal storage system. This allows the CSP plants, in contrast to PV, to uncouple the electricity generation temporal from the moment of the solar irradiation. In the case of the MEET model a thermal storage capacity is assumed for CSP to provide the power plant with up to 6.9 full load hours. Of course this storage is much to small to balance seasonal variations, but it works very efficiently for variations on a daily scale. Due to this device, the MEET model can reduce the electricity generation by CSP in times of excess electricity and charge the heat storage of the plant or use the heat storage to increase electricity generation when required. Since a CSP plant makes use of sunshine instead of a limited fuel, the MEET model make use of the CSP plants, if implemented for the scenario, to balance the current electricity generation and demand as first option of the controllable power plants. Only if the sun is shining and the thermal storage of a CSP plant has already been totally filled with heat, the CSP plant will generate electricity even if there is no need for it to avoid the wasting of this renewable energy. In this case, the electricity will be used to load the energy storage of the model region.

If it occurs that the MEET model needs even more electricity to balance the energy demand of a model region, the use of biomass power plants is the next step. Because of their fuel, these power plants are independent from the weather conditions and, due to their ideal almost neutral CO_2 balance and no nuclear waste, the biomass power has priority within the MEET model compared to the gas, coal and nuclear power plants. So the biomass power plants have the ability to be used as a kind of backup power with the level of power capacity the defined scenario allows and until the annual maximum biomass of the model area has been used (biomass potential of the model regions see tab.: 3.5).

When the power plants using renewable energy sources for the electricity production did not manage to provide enough electric power for the current demand of a model region, the nuclear, coal and gas power plants had to be used by the MEET model (see also section 3.11). Therefore each individual power plant is switched on or regulated to the point where the electricity generation meets the demand or all plants are running at full load. The MEET model has to respect the priority of using the nuclear power plants first, followed by coal and than gas power plants if it is possible, due to the minimum load and downtime[13] of the power plants given in tab.: 3.6. To keep the capacity of power plants that are needed to provide a model region with electricity as small as possible, the MEET model is not always allowed to shut down a power plant. This is the case if a power plant is switched off because there is enough electricity available, but the downtime would prohibit its anticipated reactivation some hours later. So the power plant needs to stay at its minimum load and the generated excess electricity will be given to the energy storage. But since this electricity is not actually needed, it does not count for the annual utilised capacity. The efficient use of these power plants is calculated by ignoring the excess electricity of the gas, coal or nuclear power plants that has been generated only because they were not allowed to shut down.

Finally the MEET model makes use of energy storage to balance the electricity generation and demand. The storage capacity of this energy storage is not limited by the MEET model in advance, so its required size ends as one result of a simulation. From storage periods of one hour up to a seasonal cycle all electric energy that is not immediately consumed will be stored for times of a supply deficit. The energy storage in the MEET model works with a charge- and discharge efficiency of 0.9 so that its cycle efficiency from electricity to electricity ends with $\eta_{stor} = 0.81$ as it is for modern pumped hydro power storage plants (Bünger et al., 2009).

In the case that the energy storage is empty and still more electric power is required, the storage is not allowed to become negative and therefore the model region has a deficit in its electricity supply that has to be resolved by additional power plants as described in section 3.17.

3.17. Optimisation of the power plant capacity to be installed

A goal of the MEET model is to find the minimum required power plants capacities for the mix of power plants defined by the user. This calculated setup of power plants capacities has to allow for an electricity supply without a deficit and will be used for calculating the behavior of the electricity supply system.

[13]The time a thermal power plant needs to cool down to avoid too much thermal stress on its materials before the power plant can become reactivated.

The importance of finding the smallest amount of required power plant capacity is that the resulting requirements for energy storage are very sensitive to an additional capacity of power plants as shown in section. 5.2.

To determine the effective needed amount of power plants for an electricity supply scenario, the MEET model starts with a first guess to place power plants in the way as described in section 6.1 up to a maximum number of power plants that would be needed to provide the annual electricity demand of a model region on average. After this, an iterative process (see fig.: 3.12) starts up, to the point where the generated electricity is enough to provide the model region throughout the year without a deficit or excess. However the energy storage budget has to be zero over the year because an increase of the stored energy would mean that there was more electricity generated than necessary and a decrease would mean a deficit of electricity generation. The MEET model is allowed to tolerate a maximum difference of 0.1 % between the stored energy at the first and the last time-steps of the calculations as a balanced electricity supply. With regard to the times of deficites in the electricity supply it is allowed for the MEET model to ignore a maximum of 0.01 % of the annual electricity demand which corresponds to about 50 minutes per year. This is less than one time step of the model. Having this limit in mind, the calculation for the required power plant capacities distinguish between four cases:

1. If there was a deficit in providing electricity due to reduced power plant capacities but the energy storage budget is positive, the MEET model starts the next iteration by having the amount of energy stored as it was in the last time step of the previous calculation. The following iteration will check if this additional energy given to the energy storage compensates the deficit in the electricity supply.

2. If there was a deficit in providing electricity and the budget of the energy storage is zero or even negative, it is obvious that for the next iteration additional capacities of power plants have to be installed by the MEET model. To decide how much more power plant capacity has to be installed, the MEET model uses the time series of the electricity generation and its demand for the considered period. The largest power deficit represents the amount of power plant capacity that will be installed for the next iteration.

3. If there was excess electricity and therefore the storage budget is positive, the MEET model has added more power plants than is necessary. So the model returns to the amount of power plant capacities from the iteration before the last addition of capacities. Since the power plants will not be enough to guarantee an electricity supply without deficits, the MEET model will add additional power plant capacities again, but only the half of the added amount of the last iteration. This reduction of the power plant addition will iterate until there is no more excess electricity.

4. If there is no deficit or excess of electricity and the energy storage arrives at the end of the year at the same level of stored energy as it has started with, the MEET model has found the amount of power plants that required to be installed for the considered electricity supply scenario.

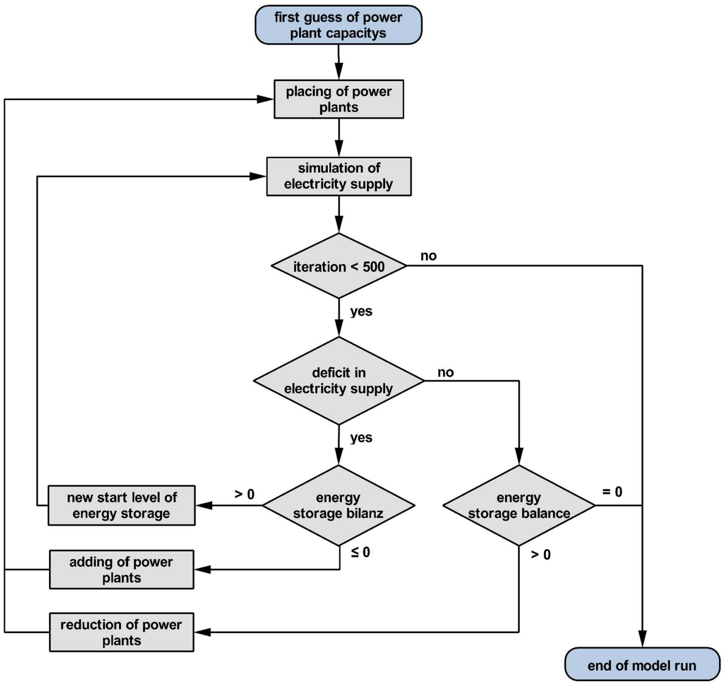


Figure 3.12.: Flow diagram of optimizing the required power plant capacities to be installed by the MEET model due to an iterative process, where the model is looking for a supply without electricity deficits and an energy storage balance of zero.

In case the MEET model does not manage to find the right amount of required power plants, it will quit after 500 iterations, to avoid endless calculations. This can be checked by the user while looking into the ’error_log.txt’ file where the number of completed iterations will be available.

3.18. Adding excess power plant capacity

The MEET model allows the user to define an ’overcapacity’-factor in percentage for the installed capacity of power plants for the supply scenario. Using this option means that after the minimum needed capacity for the electricity supply scenario has been found by the MEET model as described in section 3.17, an additional excess capacity of power plants will be added. The added capacity will depend upon the chosen percentage value and the calculated minimum needed capacity of power plants. After adding this excess capacity, one further iteration of the calculations will be carried out by the MEET model by calculating the effects of this additional power plants on the electricity supply.

The main idea of installing additional power plants to give excess capacity is to reduce the needed storage capacity due to the additional generated electricity. But not only the need of the energy storage in times of low electricity generation by power plants using weather dependent energy sources is reduced. In many other instances during the modeled time period there will be excess electricity available that could also be used if wanted.

3.19. Required input data

The MEET model requires input data of weather conditions, power curves of wind turbines, wave converter data on the setup of CSP plants to calculate the electricity generated by using renewable energy. In addition, the geographical information of the model regions and their coast lines, the electricity demand in total for each region and the hourly electricity demand is needed for input. All this data is given to the MEET model via the 'input_data' folder and can be seen or adjusted there. Finally the 'run_file.txt', a simple text document, is used to define the energy mix and other parameters for the scenarios that have to be simulated by the MEET model (appendix B.1).

The major input information the MEET model needs is weather data to calculate the potentials of generating electricity using renewable energy. To investigate the influence of the annual variation, eleven years of weather data from 2000 to 2010 have been prepared for the MEET model. This weather data come from the Modern Era Retrospective analysis for Research and Applications (MERRA) from the NASA (Lucchesi, 2012). The MERRA data are based on the Goddard Earth Observing System Model, Version 5 (GEOS-5) described by Rienecker et al. (2008) and they are reanalyze data of global weather from 1979 up to the present. They have a temporal resolution of one hour and a spacial of 1/2° latitude by 2/3° longitude. From the MERRA data, the MEET model uses the Eastward component of the wind speed at 10 m above ground in m/s (var. name: u10m), the Northward component of the wind speed at 10 m above ground in m/s (var. name: v10m), the air temperature at 2 m above ground in K (var. name: t2m), the surface air density in kg/m^3 (var. name: rhoa), the roughness length for momentum in m (var. name: z0m), the short wave solar radiation flux at ground level in W/m^2 (var. name: SWGDN) and the short wave solar radiation flux at the top of the atmosphere in W/m^2 (var. name: SWTDN).

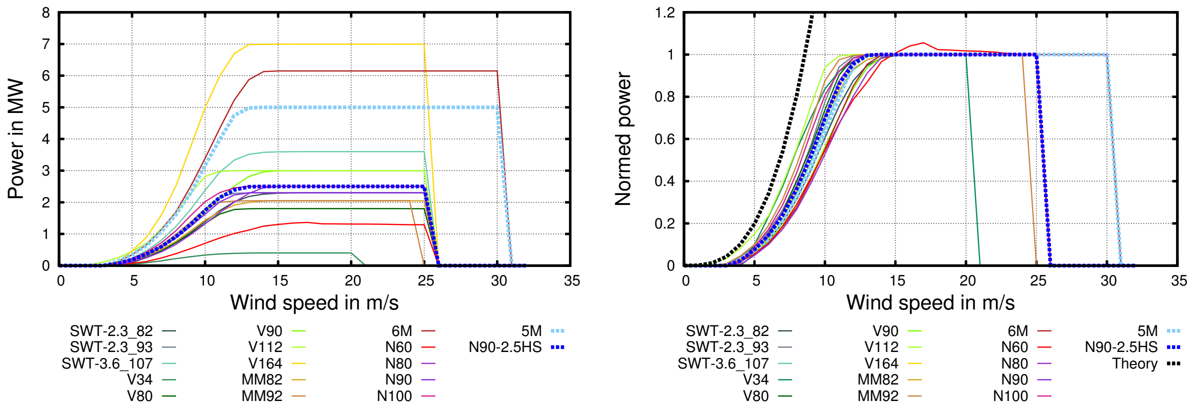
In addition to the weather data of MERRA, data of ocean waves are required. These are taken from the ERA-Interim data (Janssen et al., 1997) of the European Centre for Medium-Range Weather Forcast (ECMWF). The data is given in a six hour temporal resolution and a grid size of 1.5° latitude and longitude. A description of ERA-Interim can be found at Dee et al. (2011) and information on the wave model is given in Janssen et al. (1997). As ocean wave data, the wave height (var. name: SWHmsl) in m and of the wave period (var. name: MWPmsl) in s is used for the MEET model.

The MERRA data is available as NetCDF[14] formate and the ERA Interim data as GRIB[15] formate, which are both standard data formates for climate and weather model data. To convert them into an ASCI format the Climate Data Operators CDO tool organized by the Max Planck Institute for meteorology has been used. It is a collection of command-line operators for the work with climate and numerical weather data (Schulzweida, U., 2013). The scaling of the data to the 2.5° grid of the MEET model has been completed with the distance-weighted average remapping function of the CDO. The wave data of ERA-Interim has been interpolated from their six hour time step to a one hour time-step by using the CDO as well.

[14]Network Common Data Form

[15]General Regularly-distributed Information in Binary form

1) Wind power plant data: To calculate the electricity production by wind power, power curves of wind power plants with a typical characteristic are used for the MEET model. For onshore wind power a Nordex N90 2.5 HS is used and as offshore wind power, the power curve of the REpower 5M has been chosen. The onshore wind power plant has an rated power of 2.5 MW with a rotor diameter of 90 m and an assumed hub height of 100 m. The offshore wind power plant typically has a higher rated power, in this case 5 MW with a rotor diameter of 126 m and a lower hub height at 90 m than onshore wind power plants. Additionally, the cut of wind speed of the offshore wind power plant at 30 m/s is designed for higher wind speeds compared to the 25 m/s from the onshore wind power plant. The power curves for the onshore Nordex N90 HS is given in section 3.4 at fig.: 3.4 and for the offshore REpower 5M at section 3.5 at fig.: 3.5. To compare this used power curves with those of a variety of other wind power plants see fig.: 3.13 (a). To compare the behaviour of the power curves, all have been standardised by their rated power and the curves of the N90 (dark blue doted line) and the M5 (light blue doted line) fit quite well in the middle of the ensemble (fig.: 3.13 (b)), as it is needed for a representative power curve. But if necessary, those power curves can easily be adjusted by the user in the text-files given to the MEET model or substituted by the power curve of a different wind turbine.



(a) (b)

Figure 3.13.: (a) Comparison of different types wind turbine power curves by data of Staffell (2012). (b) Comparison of standardised wind turbine power curves to bring out the similar behaviour of different wind turbine types.

2) Wave power plant data: For the calculation of the electricity generated by wave power, the MEET model needs a power matrix of the wave power converter. In this case a 7 MW rated Wave Dragon overwhelming platform is assumed for this electricity generation. The power matrix received from the Wave Dragon developer[16] section 3.6 at tab.: 3.4. The power matrix of power output per wave height and period is given to the MEET model by an external file and can be changed easily or replaced by the power matrix of an other wave power converter type if required.

3) CSP power plant data: For the calculations of the electricity generated by Concentrating Solar Power plants, the MEET model needs an input file. This includes the rated power, the maximum heat

[16] Wave Dragon ApS; Blegdamsvej 4; DK-2200 Copenhagen; Denmark

power the power plant can deal with and the capacity of the heat storage of the modeled CSP plant (section 3.8) and so the ratio of installed collector capacity, heat power plant and heat storage can be easily adjusted in this way.

The remaining six power plant types of the MEET model do not use additional data from separated files for their specifications. Only the maximum annual available amount of bio-fuel and the minimum down time after switching off gas, coal and nuclear power plants can be changed by the user when setting up the scenario for the MEET model. The PV power specifications are oriented on a module data sheet of SCHOTT solar (2011) and can not be changed by the user, as it is part of the program code. Hydro power plants are part of the program code as well.

The geographical definition of the model regions and their coast lines come by a separate data file that includes the corresponding region for each model grid point on the 2.5° grid.

The so-called ’run_file.txt’ allows the user to define the scenarios that have to be simulated by the MEET model. Except for the seven standard model regions of the MEET model a customized rectangle region can be defined using the ’run_file’. The model grid is also defined there and can be changed as well as the temporal resolution and the temporal range of the simulation if the weather input data allows it. The energy mix for the simulation can be defined as a percentage mix of the ten power plant types. If required, an overcapacity factor can be defined, so that the MEET model builds an additional number of excess power facilities in percentage of the minimum capacity needed that was revealed by the MEET model. The maximum available biomass of the model regions is given by the ’run_file’. It gives the option to allow the model to use load management to shift demand in a specified amount over a specified number of hours. Also the use of electro mobility can be switched on and specified in terms of the number of cars, the daily kilometers driven, the accumulator capacity of the cars and the percentage of cars that are used simultaneously. For the gas, coal and nuclear power plants, the minimum down time between switching the plant off and on again is given by the ’run_file’ and can be changed easily in this way. It should be noted that all the directories to the input data can be customized at the ’run_file’ for the users PC, where the MEET model will run. A detailed description of this file for the example of a model run for Europe with a share of 60 % wind and PV power ant the weather data of 2009 can be found in the appendix B.1 and the overview of the MEET result of this simulation is presented in section 3.21 and fig.: 3.14 and 3.15.

To simulate the consumption of electricity with a realistic characteristic, data of the German electricity demand for 2008 (ENTSO-E, 2014) provided by ENTSO-E[17] is given to the MEET model (fig.: 3.3). This data with an hourly resolution in time can be scaled by the MEET model to the individual annual electricity demands of the model regions. The default used data of the annual electricity demand for the seven model regions of the MEET model are taken from the Statistical Review of World Energy by BP (2009) and can be seen in tab.: 3.3. In order to enable the user to define an individual electricity demand

[17] https://www.entsoe.eu

of the model regions to investigate future scenarios, the values can be changed in the electricity demand data file.

3.20. Additional assumptions of the MEET model

Computer models typically need to reduce the details of reality, therefore assumptions and simplifications needed to be made for the MEET model. The major restrictions of the MEET model will be shown in this section. Some are needed to make the model more usable or to reduce the requirements on the computer or some limits are given simply by the availability of the data.

The horizontal spacial resolution of the MEET model is at 2.5° latitude and longitude. This resolution is used for the weather data, the calculated potentials of the renewable energies and the positioning of the power plants using the renewable energies. Indeed this resolution seems quite large and, for example, the MEERA data would allow a resolution of 1/2° latitude by 2/3° longitude. But to simulate the details of a single power plant with the specific effects of its surroundings, much higher resolutions of data would be needed and this is not the focus of an energy supply model. It is necessary that a number of power plants work together to provide the energy needs of the simulated regions. Therefore the principal behaviour and the natural variations through the influence of changing weather and seasons are much more important than a high resolution. In this way the size of the input data stays manageable and the requirements on the computer are within the range of a typical PC[18].

Due to the high potentials of wind power in the very north and specially Greenland (compare fig. 4.3 and 4.4) and the very low population and energy demand in these regions, the MEET model does not use wind power above 60° North to avoid unrealistic high potentials. Energy intensive regions can be identified, for example, by using night time satellite images of the earth. In this case the electricity consumption can be identified by the intensity of the light, as is done in Ummel (2011). For the southern hemisphere, there is no need to do this restriction, since there is no land beyond 60°S except Antarctica, which is not considered as model region.

Regarding the transmission of electricity inside the model regions, there is a common and firm assumption of a perfect electricity grid for the MEET model. Wherever electricity is generated in a model region, this electricity is instantly and without any transmission losses anywhere in the region available. The main effects of this assumption that reduces the complexity of a simulation are a reduced need for generated electricity and in some cases a variation in the placement of power plants due to reduce transmission losses. So the transmission losses of approximately 0.3 % per 100 km for High-Voltage Direct-Current transmission (HVDC) or 1 % per 100 km for standard High-Voltage Alternating-Current (HVAC) transmission (Tenbohlen et al., 2011) are ignored. These losses in 2011 had a fraction of about 8 % of the generated electricity world wide (The World Bank, 2013).

[18] To run the MEET model at least 20 GB hard disk for input data and results and about 6 GB of RAM and a 64 bit CPU is required. Also gnuplot and ImageMagick requires to be installed.

Finally, to get electricity production and demand in balance, energy storage facilities are needed, particularly in supply scenarios with an high share of power plants using weather dependent renewable energy. Regarding the energy storage capacity, there is no upper limit by simulating the supply of the model regions. For the MEET model, a cycle efficiency from electricity to stored energy back to electricity of 0.81 is assumed. This efficiency typically corresponds to pumped storage hydro power (Bünger et al., 2009), which are at the moment the most common large storage facilities.

3.21. MEET model output

After the MEET model has managed to install the correct amount of power plants to provide all model regions with electricity as described in section 3.17, the characteristics of the given electricity supply scenario will be provided by the model output as set out in this section. In the case where the user has defined an overcapacity for the scenario as well, this will be considered by the MEET model in the way it is mentioned in section 3.18.

As a first output the MEET model generates a time series and an annual sum of the electricity generation by onshore and offshore wind power, wave power, PV power and CSP for each grid point and power plant type in the way as introduced in section 3.4 to section 3.8. That data can be found in the 'ee-energy' folder of the MEET model and the data format is a simple text file (for an example see appendix B.2). Additionally, binary data files (*.bin) for the power plants are provided, showing the generated kilowatt hours per year and kilowatt peak power for each grid point. Together with a description file (*.ctl) they can be used to generate maps[19] of the potential of renewable energies as given in fig.: 4.1 to fig.: 4.5.

In the main folder of the MEET model there can be found a text file called 'error_log.txt' after each model run. This should be checked, since it offers the user information for the case that something was incorrect with the calculations. So the number of each iteration step is followed by the information if the storage or power plant capacity needs to be adjusted for the next iteration. Moreover, when there is not enough space in a model region to place on site the required number of power plants, a warning message is generated, or if a mistake by the scenario definition has been made and the sum of the power plant shares is not 100 %.

The main output of a model run can be found in the folder 'output_data'. A binary data file combined with a description file (*.bin and *.ctl) for each power plant using weather dependent renewable energy is created to generate a map that will show how much power plant capacity has been placed by the MEET model in the grid cells of a model region as used for fig.: 6.1.

Text files, named with the power plant type followed by '_efficiency.txt', indicate the number of grid cells available in a model region to install this power plant type and the corresponding efficiency of use of the power plant can reach at this grid cells (for an example see appendix B.2). So one can work out how the degree of utilised capacity of added power plants will be reduced due to the increased use of grid cells with a low potential of renewable energy (compare also fig.: 3.7 to fig.: 3.11).

[19] The data can be plotted by using for example a software such as the Grid Analysis and Display System OpenGrADS.

As one of its most important outputs, the MEET model generates a comma-separated values data file (*.csv) for each model region. Those files are named as ’results_region#_energy.csv’ while # represents the model region number and include hourly values of the electricity generated by all power plant types for the whole range of the simulated scenario as well as the electricity demand and the energy stored in the energy storage (for an example see appendix B.2). This time series are given in the sequence and labelled in the file as followed: ’el_sum_wind_hist’ for the electricity generated by onshore wind power plants, ’el_sum_atom_hist’ for nuclear power plants, ’el_sum_coal_hist’ for coal power plants, ’el_sum_gas_hist’ for gas power plants, ’el_demand_hist’ for the demand for electric energy, ’el_storage_hist’ for the temporally stored energy, ’el_storage_hist_power’ for the electricity given to or taken from the energy storage, ’el_import’ for the deficit of electric power, ’el_sum_pv_hist’ for the electricity from PV power plants, ’el_sum_wind_offshore_hist’ for offshore wind power plants, ’el_sum_wave_hist’ for wave energy converters, ’ev_loading_hist’ for the electricity given to the batteries of electric cars, ’ev_akku_state_hist’ for the energy that is stored in the batteries of electric cars, ’el_sum_hydro_power_hist’ for runoff hydro power plants, ’el_sum_bio_hist’ for biomass power plants and ’el_sum_csp’ for the electricity generated by csp plants. An example for this major output can be found in appendix B.2.

Finally the results of the MEET model will be summarised in a html file together with graphics plotted by making use of the program ’gnuplot’. An example of this output that will appear in a web-browser window after the MEET model has finished the simulation is given by fig.: 3.14 and fig.: 3.15 showing the results for Europe with a scenario having a share of 60 % of renewable energy using power plants (the specifications made for this scenario can be found in the ’run_file.txt’ presented in appendix B.1). Starting with fig.: 3.14, the ’HOME’ button at top right will lead to a menu to choose the model region of interest, in this case, the region of Europe is selected. The name of the model region is then given below, followed by two arrow buttons to navigate through the time series of the modelled scenario in a two-week time-step. The number of the selected calendar weeks is shown on the right side to the navigation arrow buttons. An hourly development of the electricity supply, starting with the first hour of the selected two weeks, is given by the following three graphs below in fig.: 3.14. The individual hourly generated electricity of the specific power plant types, the sum of hourly electricity generation, the electricity demand and the electricity going to or coming from the energy storage is given in the first graph. A cumulated view with filled curves of the electricity generation is given by the second graph and the third graph represents the hourly development of the stored energy. Below this, the overview of the whole year commences with two graphs for the percental frequency distribution of the filling level of the energy storage during the hours of the modelled period. The first as percental counts per stored energy bin and the second as cumulated percental counts per maximum used storage capacity.

The text below the mentioned graphs in fig.: 3.14 differs between the maximum, minimum and effective stored energy in GWh required for the simulated scenario. Typically, the minimum stored energy should be zero and the maximum and the effective stored energy should be equal. But in the case of a scenario having excess power plant capacity, the energy storage might not become zero and all excess electricity will be stored at the electricity storage. To see the effective required energy storage capacity, the MEET model calculates this effective capacity the energy storage would need to guarantee the electricity supply while ignoring the remaining excess electricity. The maximum occurred power over the year for the energy storage is also given below in GW.

Going further down on the html page (fig.: 3.15), the amount of emitted CO_2 by gas and coal fired power plants in kg per year is shown. Next there is given the degree of capacity utilisation and the installed power plant capacity in kW for all power plant types of the MEET model. The gas, coal and nuclear power plants also have an 'effective use' for there utilised capacity, ignoring the electricity that has been generated just to avoid a shut down of the power plants as described in section 3.16.

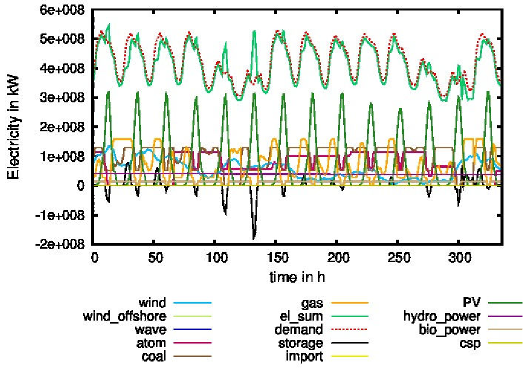
At the end of the MEET output overview on the left side, a graph of the annual load duration curve of the electricity demand is given (red line). It shows the time a certain electric power is minimum asked during the year. Additionally, the generated electricity by the renewable energies using power plants and the gas, coal and nuclear power plants as residual is shown at the hour of the given electricity demand. The last graph on the right hand side of the results page, gives an overview of the electricity supply for the whole year as the accumulated power for all power plant types. While looking at these last two graphs one should consider, that it is hard to see the variations of electricity generation during one day on this timescale as it occurs, for example, for the variation of PV power between night and day.

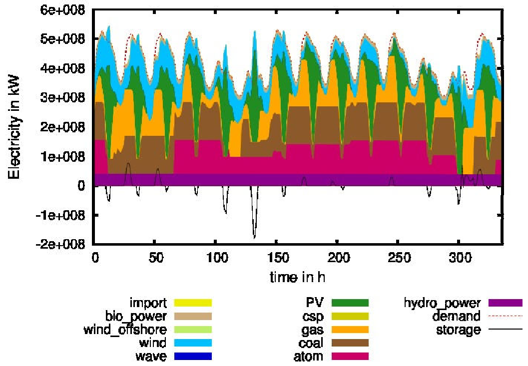
So the data calculated by the MEET model in the way presented in this section form the base to analyze the behaviour of different electricity supply systems as done in the following sections of this thesis.

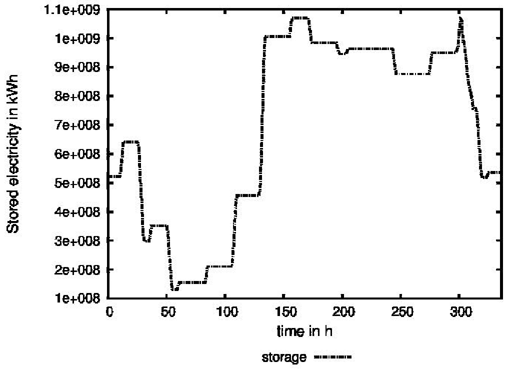
HOME

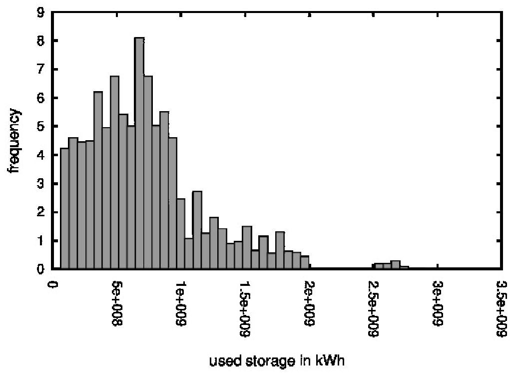
Europe

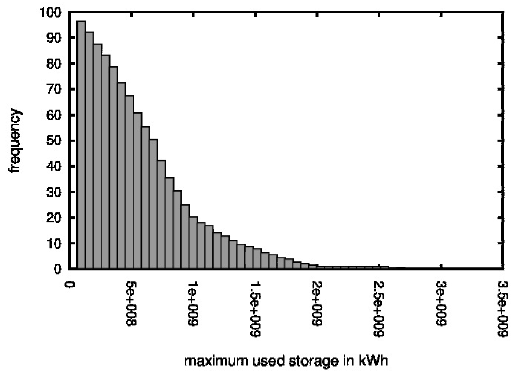
← → 31_32











Needed storage capacity in GWh:
Maximum stored energy 3221.1255
Minimum stored energy 0.0000000
Effective stored energy 3221.1138559999999

Maximum needed power gradient of storage in GWh/h 232.21899

Figure 3.14.: Example of MEET model html web-browser output (1/2). The results for Europe are based on weather data of 2009 and the scenario considers a mix of power plants with a 60 % share of wind and PV power. The detailed scenario settings in the 'run_file.txt' can be found in appendix B.1. At the top, the electricity supply of calendar week 31 and 32 can be seen as well as the stored energy followed by histograms of the energy storage use and information about the total required energy storage capacity.

Amount of emitted CO_2 for the modeled time in kg:
by coal 7.61500336E+11
by gas 2.70177599E+11
total 1.03167794E+12

Capacity utilisation:
use of windplants 0.32704666
instaled windpower in kW 2.58912496E+08
use of windplants offshore -
instaled windpower offshore in kW 0.0000000
use of wave converters -
instaled wave power in kW 0.0000000
use of photovoltaics 0.12909422197833828
instaled PV in kW-peak 6.04131520E+08
use of csp plants -
efficient use of csp plants -
instaled csp power in kW 0.0000000
use of hydroplants 0.29996532
instaled hydro power in kW 158224944
use of biomasplants 0.90048087
instaled bio power in kW 14380000.
use of atomplants 0.59316403
efficient use of atomplants 0.57843077
instaled atom power in kW 1.15000000E+08
use of coalplants 0.70988995
efficient use of coalplants 0.70129454
instaled coal power in kW 1.29000000E+08
use of gasplants 0.43384328
efficient use of gasplants 0.43384328
instaled gas power in kW 1.58100000E+08

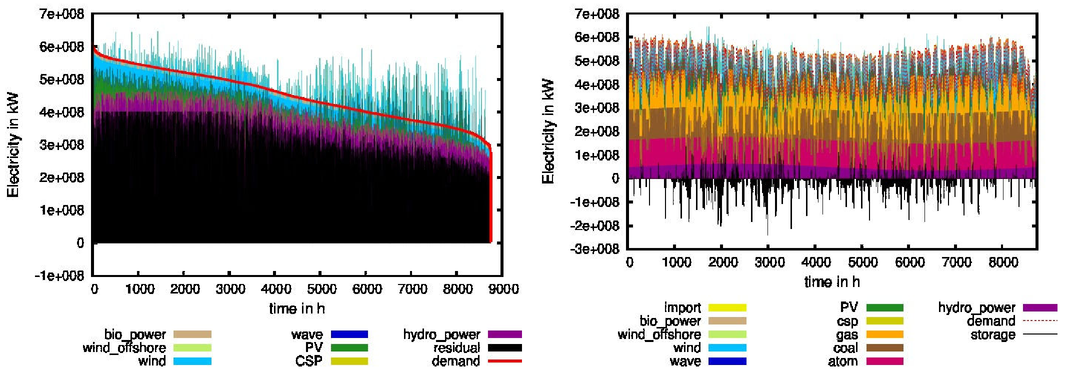


Figure 3.15.: Example of MEET model html web-browser output (2/2) with the same settings as in fig.: 3.14. This part of the output page provides the CO_2 emitted by fossil fuel burning power plants followed by the installed power plant capacities and their degree of utilised capacity. At the bottom, the annual duration curve of electricity demand and the overview of the electricity generation during the year is given.

4. Validation of the MEET model

The electricity supply and its behaviour in a region or even a continent is a complex system that depends on a large variety of components. Of course a computer model for analyzing such an electricity supply system will not manage to represent the reality or forecast a future electricity supply in all its details, but it will help to better understand of dependencies of the components of the electricity supply.

To get an idea of the quality of the model results and the conclusions that can be drawn on the results, a validation of the computer model is needed. Therefore section 4.1 provides a general overview of the potentials of power plants using weather dependent renewable energies. In section 4.2 a comparison of individual power plants simulated by the MEET model with existing power plants was made. Further the MEET model power plants have been compared with German EEG feed-in data and otherwise simulated data on different time scales. Finally, the calculations of the MEET model for energy scenarios created by other energy models have been compared in section 4.3. Also the electricity supply of Europe for the year 2007 has been simulated by the MEET model to illustrate its behaviour against actual data.

4.1. Potentials of renewable energy in the MEET model

Considering the basics of the global weather system and the circulation of the atmosphere, the structures of resulting potentials of renewable energies have to be found as well in the electricity generation by power plants using this renewable energies in the MEET model. In this case it affects the distribution of the simulated potentials of CSP, PV, wind and wave power. For that reason the mean annual electricity generation calculated by the MEET model for the years 2000 to 2010 and the standard deviation relative to this generated electricity has been plotted on a map in fig.: 4.1 to fig.: 4.5 to identify the main structures.

Since the geographical latitude, where the sun passes its zenith, varies between 23° 26’ south to 23° 26’ north during its annual cycle and most solar radiation reaches the earth at the equator and becomes less when going towards the poles, the resulting energy difference needs to be balanced by the circulation of the oceans and the atmosphere. The transport of energy in terms of latent and sensible heat to the poles by the atmospheric circulations is done by three main circulation cells per hemisphere called the Hadley-, the Ferrel- and the Polar- cell. Each cell covers approximately 30° of geographical latitude. Around the equator warm air rises to the top of the troposphere at about 15 km height and forms a lot of clouds. This is called the Inner Tropical Convergence Zone (ITCZ). At approximately 30° geographical latitude the air descends and streams back to the equator at the lower troposphere[1]. The downward motion of the air

[1] The troposphere is the atmospheric layer of the lowest 8 km to 15 km high where our weather takes place.

dissolves clouds and forms the high pressure belt and the air streaming back to the equator creates the trade winds. Between 30° and 60° geographical latitude, the atmosphere is dominated by the west wind zone with its high and low pressure weather systems, followed by the polar cell from 60° to 90° latitude with cold down drafts at the poles. This characteristics of solar irradiation, production of clouds shading the sun, the wind system, ocean wave generated by the wind, and geographical structures such as land sea distribution and mountains form the distribution of the potentials of renewable energies.

To check the distribution of renewable energy potentials for the MEET model the annual electricity generation of the calculated years 2000 to 2010 is plotted for all grid cells as the average of the annual generated kWh per installed power in kW or as mean full load hours. The variation in the electricity generation between the years is given as the standard deviation relative to the mean electricity generation of the individual grid point to get an idea about the longterm variability:

$$\sigma_{rel} = \frac{\sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (E_i - \bar{E})^2}}{E} \qquad [4.1]$$

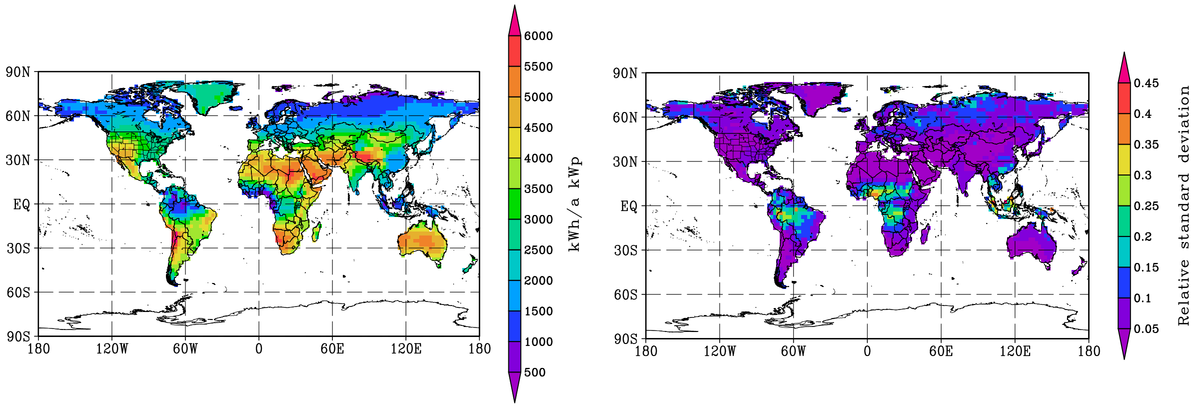
with n the number of years, E_i the electricity generated in one year and $\bar{E}$ the averaged electricity generation of the n years.

The potentials of generating electricity by CSP plants as represented in the MEET model, distribute as given in fig.: 4.1 (a). As one would expect, the highest potential for CSP plants are at lines of latitude of about 30° north and 30° south. In this typically dry and cloudless regions, having a high share of direct solar radiation, the CSP plants of the MEET model reach an annual electricity generation of 5000 to 6000 full load hours. This high utilised capacity is possible due to the heat storage, having a capacity of 6.9 full load hours, and the solar multiple of 2.5 for the simulated CSP plants (section 3.8). Especially the solar multiple of the solar collector field enable the CSP plant to collect enough solar power to run the comparatively low rated power of the generator unit even in times of no perfect irradiation conditions. The dry deserts as the Mojave and the Sonoran in north America, the Sahara in north Africa and the Arabian desert, the Atacama desert in Chile, the Kalahari in South Africa and the most parts of Australia offer particularly good potentials for CSP plants.

Regions having a high topography and specially mountains such as the Himalaya and the Andes can be identified with a high potential for the CSP plants. Even Greenland, with large areas around 2000 m of altitude and higher, reaches up to 3000 full load hours, which is quite high compared to other regions of that latitude. A reason for this phenomenon is that the light absorbing and scattering air mass of the atmosphere is reduced by approximately 50 % for each 5.5 km of altitude (Roedel and Wagner, 2011).

Along the equator there is a heavy reduction of the potential of CSP plants (fig.: 4.1 (a)) due to the ITCZ with its convective clouds. Because clouds reduce especially the direct radiation, this mainly effects the CSP plants and not the PV power plants (fig.: 4.2 (a)).

The variation in the electricity generation between the years is given in fig.: 4.1 (b) and the highest variation of 20 % and more occurs along the equator due to the influence of the ITCZ, which varies the position from year to year. But the weather of the west wind zone also leads to an increased variability of the annual electricity generation by csp plants.



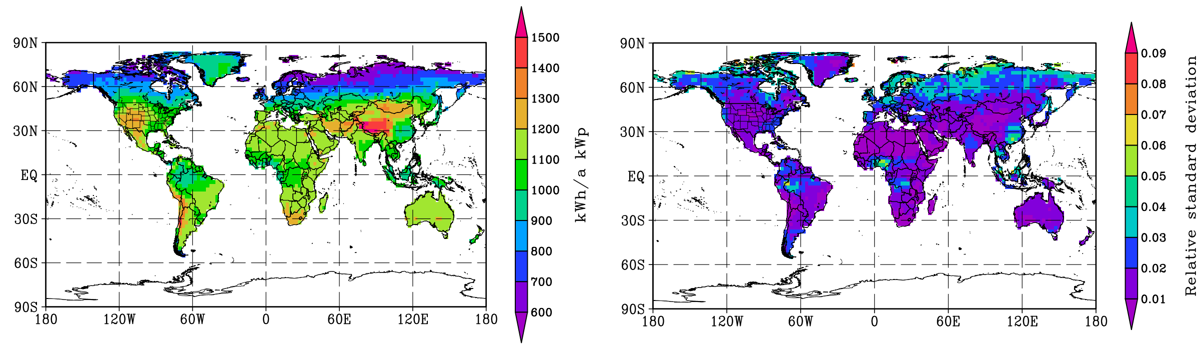
(a) (b)

Figure 4.1.: (a) Distribution of annual mean CSP potentials of MEET for the years 2000 to 2010. The thermal energy storage of the CSP and the solar multiple of 2.5 for the collector field in relation to the rated power enable high full load hours. (b) Relative standard deviation of CSP potentials.

The main structures of the potentials of PV power plants (see fig.: 4.2 (a)) look much the same as those of the CSP plants, but the regional differences are not that large. So the potentials in hot areas like the Sahara or Australia are not that remarkable since the efficiency of PV-cells decrease with the temperature. On the other hand side, the influence of clouds at the ITCZ and the west wind zone dose not have such a heavy influence, since the PV cells are able to use the diffuse fraction of the solar radiation as well. Therefore most regions offer values of full load hours in the range of 800 h to 1300 h. High mountainareas, and Greenland again, come out with a good potential due to the reduced atmosphere that would absorb irradiation and in this case the cold air temperatures that cools the PV-cells as well.

It is interesting to note the low variation of the annual generated electricity by PV power plants (see fig.: 4.2 (b)) compared to all other weather dependent renewable energy using power plants. The highest values of the relative standard deviation are at the equator as well but also above 60° north, where the potentials are very low except in Greenland.

The distribution of the potentials of onshore wind power plants (see fig.: 4.3 (a)) is clearly dominated by the west wind zones of the northern and southern hemisphere. Greenland comes up with a very high potential due to the polar winds and the high level of the ice shield. Often coastal areas are favoured but large parts of the inner continents also reach values around 2500 full load hours. So the inner plains of the US, central Europe, Australia and South America and also the trade winds in the Sahara offer good conditions for wind power plants. By contrast, the ITCZ comes up with poor conditions and a high relative variation of the annual electricity production (see fig.: 4.3 (b)). At the main areas for wind power plants, the relative standard deviation is at the range of 10 % of the annual mean electricity generation.



(a) (b)

Figure 4.2.: (a) Distribution of annual mean PV power potentials of MEET for the years 2000 to 2010. (b) Relative standard deviation of PV power potentials being remarkably low compared to CSP in fig.: 4.1.

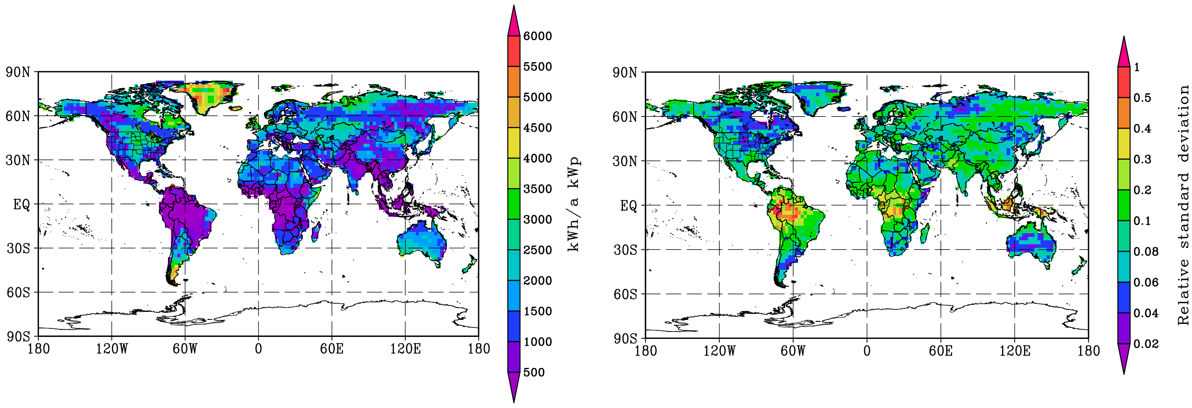
For the offshore wind power plants, where the surface roughness is low and no mountains to influence the wind field, the west wind zones reach the highest values of full load hours with 5000 h at the northern hemisphere and 6500 h at the southern hemisphere, where there is less land to reduces the wind speed (see fig.: 4.4 (a)). Along the coasts the potentials are typically reduced and specially along the ITCZ the potential is poor.

Regarding the variability of the electricity generation by offshore wind power plants, the west wind zones offer a quite constant regime (see fig.: 4.4 (b)). The main relative variability occurs around the ITCZ and specially at the Walker circulation on the Pacific ocean between south east Asia, Australia and middle and South America. This circulation varies in its intensity from year to year from the weather phenomena El Niño and La Niña.

Similar to the potentials of offshore wind power plants results in the distribution of the potential of wave energy converter since the ocean waves are created by the wind. So the wide open ocean in the west wind zones offers the highest potentials with 4000 to 6000 full load hours. The influence of coast lines, specially if they are located where the wind is coming from, can be seen in the case of south America (see fig.: 4.5 (a)). Also a smaller sea like the Gulf of Mexico or areas with numerous islands as in southeast Asia have a strong reduction in their potential.

The highest values of the relative standard deviation for the annual generated electricity by wave energy converter occur at the polar sea, where the variation in sea ice has a dominant influence.

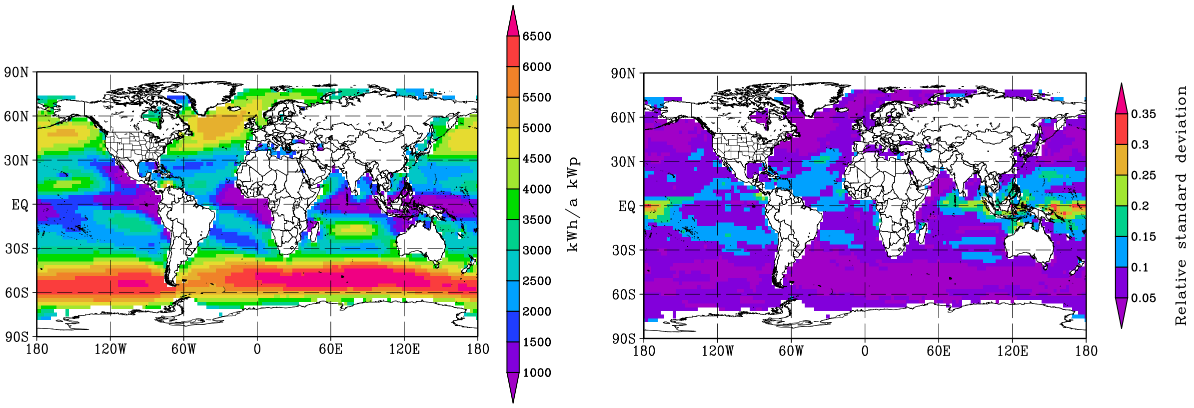
Of course very many regions of high potential for electricity generation are not realistic locations to place a power plant. For example the middle of an ocean, a desert or even Greenland, since there is little or no demand for electricity and a transmission to the next region of high electrical demand seems unrealistic at present. But still it is good to get an understanding about the global distribution of the potentials of weather dependent renewable energies. On the other hand, very many big cities are located close to coasts where wind, waves and sun are often available and even to transmit electricity



(a) (b)

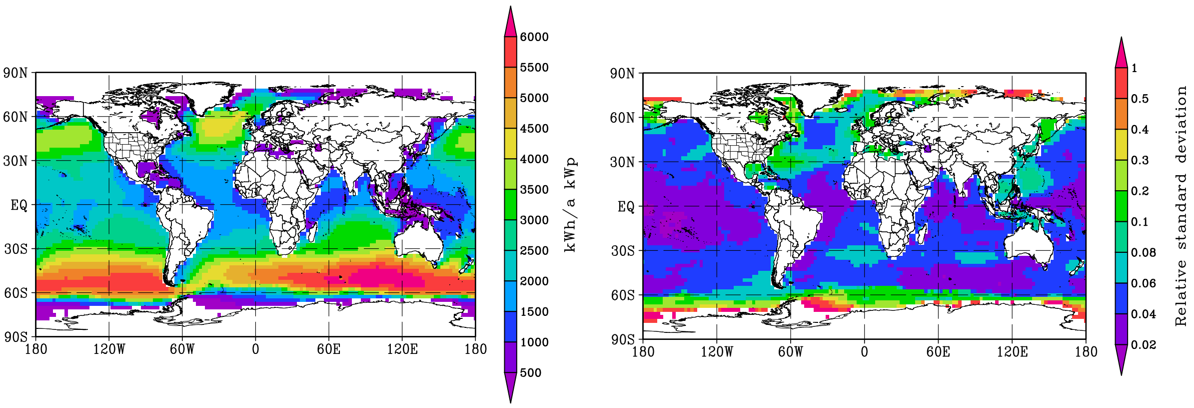
Figure 4.3.: (a) Distribution of annual mean onshore wind power potentials of MEET for the years 2000 to 2010 providing the highest potentials in the west wind zone and on Greenland. (b) Relative standard deviation of onshore wind power potentials.

over 1000 km or more from a desert is not out of range as, for example, the DESERTEC foundation proves (Knies et al., 2009).



(a) (b)

Figure 4.4.: (a) Distribution of annual mean offshore wind power potentials of MEET for the years 2000 to 2010 showing the west wind zone and the effect of a wide open sea on the southern hemisphere. (b) Relative standard deviation of offshore wind power potentials.



(a) (b)

Figure 4.5.: (a) Distribution of annual mean wave power potentials of MEET for the years 2000 to 2010 showing the same structure as the offshore wind in fig.: 4.4. (b) Relative standard deviation of wave power potentials with high values at sea ice regions.

4.2. Quality of power plant simulation in the MEET model

Considering the boundary conditions on which the MEET model calculates the theoretical electricity generation by power plants using weather dependent renewable energies for each grid cell (for details see section 3), it becomes obvious that the model will not simulate the exact amount of generated electricity. To evaluate the results, they have been compared in this section with data of existing power plants.

Ideally, one would compare the results of the MEET model for a lot of grid cells all over the world with existing power plants on a hourly scale. But since this kind of data is rare or even not accessible, regarding CSP plants or wave energy converters, this check has been reduced to only a few cases to give an idea about the quality of the model results. As already mentioned it is not the aim of the MEET model to simulate a single plant as perfectly as possible but to represent the behaviour of the electricity supply by the power plants correctly.

4.2.1. Validation of CSP plant modelling

Parabolic CSP plants have been quite rare up to now and have been built mainly in Spain and the south-west of the USA. The older CSP plants are combined with a fossil fuel fired unit to get the power plant independent from the weather conditions and can therefore not be compared with the CSP of the MEET model. Even the modern CSP plants have the ability to be independent from the solar radiation in a certain range due to their thermal storage. So the electricity generation can be customized and this makes it hard to compare the electricity generation on a hourly base with those calculated by the MEET model.

Because the CSP plant defined for the MEET model is almost set up in the way as the Andasol CSP plant in Spain, its annual electricity generation has been compared to validate the calculations. The Andasol CSP plant is located at 37°13’ N and 3°04’ W and runs about 3500 full load hours a year (Solar Millennium AG, 2008). For this location the MEET model calculates an annual mean for the years 2000 to 2010 of 3900 full load hours with a standard deviation of ± 175 full load hours as one sigma range. So they differ by about 10 %, but regarding the standard deviation and the fact that the indicated 3500 full load hours are only a approximated number without the information of a specific year, the MEET result is an acceptable agreement.

4.2.2. Validation of PV power plant modelling

Photovoltaic modules are widely spread for electricity generation and specially since the invention of the EEG their number has been rising rapidly in Germany. As it is part of the EEG that the energy providers have to publish the annual feed-in by the power plants belonging to the EEG, this data offer a good base for a comparison with the results of the MEET model.

To make sure that the model is not optimized for one grid cell of a specific year, two reference areas and the years 2009 and 2010 were chosen for the validation. The test areas should not be too close together and well represented by grid cells of the MEET model. The German federal states Rheinland-

Pfalz and Brandenburg were compared with the grid cells having the center at the coordinates 50°00' N 7°30' E and 52°30' N 12°30' E.

The data of the annual electricity feed in and the installed peak power of each PV power plant is available from the Amprion GmbH at http://www.amprion.net for Rheinland-Pfalz and from the 50Hertz Transmission GmbH at http://www.50hertz.com for Brandenburg. Since there are thousands of PV power plants and the data bases also include data of low quality or even incorrect information, extreme values in the data set that differed from the average value by more than the standard deviation were ignored, which is a similar approach to Buchmann (2012). Following this procedure, Rheinland-Pfaltz has an averaged value for the full load hours of PV power plants for 2009 with 943 h ±288 h for the one sigma range and for 2010 with 866 h ±147 h. The corresponding full load hours for the grid cell (50°00' N 7°30' E) of the MEET model are 916 h for the year 2009 and 887 h for 2010. The results of the EEG data for Brandenburg are 867 ±89 full load hours for 2009 and 806 h ±94 h for 2010 while the grid cell (52°30' N 12°30' E) of the MEET model delivers 847 full load hours for 2009 and 812 h for 2010. This shows a very good behaviour of the modelled PV data and the overall difference of measured electricity generation to the modelled results with just about 1 % for the given data.

Additionally the data of the MEET model has been compared with calculations made by the PVGIS project (Súri et al., 2008; Huld et al., 2012) on http://re.jrc.ec.europa.eu/pvgis, where the electricity generation for customized PV-setups and locations can be calculated. For a 30° tilted PV-modul facing south, PVGIS calculates for the position 50°00' N 7°30' E 890 full load hours and for 52°30' N 12°30' E 859 full load hours. This fits to the results of the MEET model as well, but these values are mean values and not for a specific year.

4.2.3. Validation of onshore wind power plant modelling

The use of wind power for electricity generation is quite common and so there already exist very many power plants. In the same way as for the feed-in of PV power, the EEG data includes the annual electricity generation by wind power plants. To get rid of extreme and even obviously wrong feed-in values, the EEG data for wind power has been treated in the same way and for the same regions as for the PV data described in section 4.2.2.

The EEG data for Rheinland-Pfalz[2] from amprion leads to an average amount of full load hours of 1400 h with an one sigma range of ±372 h for the year 2009 and with 1188 h ±190 h for the year 2010. The corresponding grid cell of the MEET model at 50°00' N 7°30' E has 1484 h for 2009 and 1348 h for 2010. EEG data from 50Hertz of Brandenburg[3] offer slightly better conditions for wind power plants and had 1425 ±204 full load hours in the year 2009 and 1388 h ±190 h in 2010. Since the grid cell of the MEET model at 52°30' N 12°30' E comes close to the Baltic Sea in the north, the potential of wind power calculated by the MEET model tend to high values of 1748 full load hours 2009 and 1712 h in

[2]Data for Rheinland-Pfalz from http://www.amprion.net

[3]Data for Brandenburg from http://www.50hertz.com

2010. Therefor the ratio of 0.86 for the electricity generation by wind power plants of the EEG data compared to the results of the MEET model seems to be relatively low. An additional fact why the MEET model overestimates the electricity generation by wind power plants compared to the existing plants is that the hub height of modern wind power plants is rising to heights around the value that has been assumed in the MEET model with 100 m above the ground. Because the wind power depends on the power of three of the wind speed and this is rising with the height above the ground, higher wind turbines will generate more electricity than the lower plants that were built ten or more years ago.

Furthermore the over the years 2008 to 2010 averaged full load hours for the wind power plants of the amprion and 50Hertz area given in Pfaffel et al. (2012) reach the same range of values. The 1400 h (1474 h for MEET) and the 1550 h (1819 h for MEET) are 5 % and 15 % lower than the results of the MEET model. But, including the latest capacities, they reach values of 1500 and 1750 full load hours which is fitting quite well to the MEET model and shows that it represents the upcoming generation of wind power plants.

4.2.4. Validation of offshore wind power plant modelling

The wind park Alpha Ventus is Germany's first offshore wind park and it commenced its electricity generation in Apr. 2010. Its location is 45 km north from the island of Borkum and the coordinates of the centre are 54°0' N and 6°35' E. The wind park is formed by 12 wind power plants of which six are of the type REpower 5M as it is considered for the MEET model as an offshore wind turbine. For the year 2011 Alpha Ventus worked with 4450 full load hours (Bartsch, 2012). As the offshore wind park is too young for a direct comparison with the MEET model that covers the years 2000 to 2010, the generated electricity has to be seen in relation to the averaged electricity generation over the years calculated by the MEET model. The corresponding grid cell results with 4200 full load hours as average and a standard deviation of $\pm$277 full load hours, which is totally in range.

4.2.5. Validation of wave energy converter modelling

Since wave energy converters are not common, there is no data for the electricity generation of an existing power plant available. But a study from Fairley and Willis (2012) uses data from wave buoys to calculate the potentials of wave energy converters. This calculated potential of electricity generation should be quite close to a real power plant, as it uses ocean wave data measured directly at the place where the wave energy converter could be installed. The 7 MW rated Wave Dragon wave energy converter that is implemented to the MEET model has also been considered in the study of Fairley and Willis (2012) and can therefore be compared directly.

The wave buoy is located at Wave Hub, a region intended for offshore power plants 16 km from the north west coast of Cornwall in England with the coordinates 50°18' N and 5°31' W. As a measurement period the time from Oct. 2009 to Oct. 2010 has been used and has lead to an annual electricity generation of 1461 full load hours. The MEET model comes up for the grid cell including this coordinate with

1867 full load hours for the same period and with 2050 full load hours as average for the years 2000 to 2010 with a standard deviation of ± 287 full load hours. So the results are in range, but clearly the MEET model tends to overestimate the potential of wave power. This could be explained by the fact that an offshore power plant will be placed some kilometers from the coast as it was 16 km in this case, but the center of a offshore grid cell from the MEET model could be up to 125 km away from the coast which will tend to have waves carrying more energy.

Finally the comparisons in the sections above showed, that the power plants using weather dependent renewable energy for the generation of electricity are well represented at the MEET model. Of course those control samples do not guarantee perfect calculations by the MEET model for all grid cells on the globe, but this is not even the focus. Especially grid cells located on a coast line might over or underestimate the conditions of that site, as the large area covered by a grid cell might be dominated by the land or the sea conditions. Section 4.1 showed a reliable distribution of the electricity generation potentials and section 4.2 proved the right order of electricity feed-in. The temporal behaviour of these power plants on the hourly scale is mainly given by the reanalyzed weather data of MERRA (Rienecker et al., 2008) and ERA-Interim (Dee et al., 2011) that has been quality checked and therefore allow the MEET model a good calculation of time series for the modeling of electricity supply scenarios.

4.3. Comparison of MEET model results with other electricity supply scenarios

To see how the different types of power plants interact on varying scenarios of electricity supply, seven scenarios from other studies were modelled with the MEET model by defining the same power plant mix for the simulations (the used power plant mix are given in tab.: 4.1 to 4.7). These scenarios reach from a set up of the present to an electricity supply that is highly dominated by power plants using renewable energies. The focus of the model comparison is on (a) the capacity factor (b) the generated electricity by each power plant type and (c) the annual load of the power plants. Referring to (a) it is the ratio of total installed power plant capacity to the annual mean power being required for the electricity demand. With reference to (b) the generated electricity by power plant type is given as the percentage of the total generated electricity. The annual load of the power plants (c) is presented as full load hours. An overview of the results calculated by the MEET model and the original scenarios is given in the tables 4.1 to 4.7 and additionally for the full load hours by fig.: 4.6 (a) and (b). For the MEET model, the model region of Europe were chosen as the reference region for the comparison and the driving meteorological data where adopted to the year of the scenario or, alternatively, the data of the year 2009 were used for scenarios of the future, where weather data are not available.

The first study used for the comparison is called energy '[r]evolution - A sustainable world energy outlook' (Teske et al., 2012) and refers to the region of Europe. The scenario 'Europa27 Referenz 2009' (tab.: 4.1) represents the power plant mix of Europe in 2009 and is clearly dominated by gas, coal and nuclear power plants. As an intermediate scenario the 'Europa27 Referenz 2050' (tab.: 4.2) and, as a renewable scenario, the 'Europa27 [r]evolution 2050' (tab.: 4.3) setups have been chosen.

The second study has its focus on the German electricity supply and is called 'Energiestudie' (Lanz et al., 2009). The study does not include a scenario dominated by the use of renewable energies for the electricity supply, but scenarios representing the past and the near future called 'Energiestudie 2007' (tab.: 4.4) and 'Energiestudie 2020' (tab.: 4.5).

As the third study the 'Leitstudie 2010' (Nitsch et al., 2010a,b) has been used which considers the region of Europe and the very north of Africa for an additional use of solar power. There the data of a scenario of the past called 'Leitstudie 2009' (tab.: 4.6) and a scenario mainly based on renewable energies for the electricity supply called 'Leitstudie 2050' (tab.: 4.7) have been chosen for the comparison.

The simulations by the MEET model were initialised with the power plant mix of the scenarios to investigate. Once the share of the power plant capacities in percentage values of total installed power plant capacity (see column 'power' in tab.: 4.1 to 4.7) have been given to the MEET model, the absolute number required power plant capacity, the generated electricity per plant type and its full load hours were calculated by the MEET model for the comparison and summarized in the mentioned tables. For the three historical scenarios Europa27 Referenz 2009 (tab.: 4.1), Energiestudie 2007 (tab.: 4.4) and Leitstudie 2009 (tab.: 4.6) with an electricity supply largely based on gas, coal and nuclear power plants, the MEET model generally installed less power plant capacities related to the annual required electric energy than the given scenarios. For the MEET model this results in a capacity factor (installed power plant capacity divided by the annual mean required electric power) of 20 % to 30 % less than the capacity factor of the given scenarios. So obviously the MEET model tends to a higher use of the gas, coal and nuclear power plants or the given scenarios where setup with a higher power capacity than actually required.

Mainly the nuclear power plants reached full load hours too high in the MEET model, while the share of generated electricity fits quite well. This is based on the use of this power plants for the base load and their priority of use against coal and gas power plants. Since the capacity of nuclear power plants in the scenarios is less than the lowest point of the electricity demand curve, it is not obvious where the low utilised capacity of the other models comes from because there is almost no need for a power reduction or shut down of the nuclear power plants. Almost the same is given for the coal power plants. Only the gas power plants which are the last at the order of use, meet the full load hours of the other scenarios.

Adapting the MEET model to the same capacity factor (same ratio of power plant capacity and electricity demand) of the scenarios by using the option of installing excess power plant capacities to the MEET model shifts the nuclear and coal power plants closer to the level of full load hours simulated by the other models. This can be explained as now a higher power plant capacity is available to provide still the same electricity demand. But a comparison with the values of full load hours for Germany's nuclear = 7640 h, coal = 5075 h and gas = 3210 h power plants of 2011 (et-Redaktion, 2012) shows that again the MEET model overestimates the utilised capacity of nuclear power plants, but all scenarios of the other models clearly underestimate it. So every scenario does not meet the detailed reality and even the original data from et-Redaktion (2012) has a shift as some power plant capacities get into- or out of use during the year.

For the part of the power plants using renewable energies, the MEET model overestimates the full load hours of PV and specially wind power plants. This occurs because the MEET model uses the best sites first, which leads especially for scenarios with a low share of renewable energies to a high utilised capacity. But on the other hand the Leitstudie 2009 underestimates the full load hours of wind power with 1489 h compared to the data for Germany of et-Redaktion (2012) with 1650 h, and for the utilised PV capacity the Energiestudie 2007 also underestimates the value of 970 full load hours (et-Redaktion, 2012).

Regarding the two intermediate scenarios Europa27 Referenz 2050 (tab.: 4.2) and Energiestudie 2020 (tab.: 4.5), the MEET model came up again with a lower capacity factor than the given scenarios and uses especially the coal power plants more often. The increased share of electricity generated by coal power plants compensates the reduced share of the gas power plants, so that the sum of gas, coal and nuclear power plants end up with a comparable share for the electricity supply as the given scenarios. Most of the renewable energies using power plants fit quite well for this case due to the strong increase of the full load hours of PV power from 788 h to 1314 h and for wind power from 1840 h to 2978 full load hours for the Energiestudie 2020 scenario.

For the two renewable based scenarios Europa27 [r]evolution 2050 (tab.: 4.3) and Leitstudie 2050 (tab.: 4.7) on should mention, that now the MEET model has a lower capacity factor than the given scenarios. This is mainly based on the high full load hours of CSP and bio power plants at the given scenarios. Therefore the remaining coal and gas power plants have increased full load hours and share of generated electricity compared to the scenarios. For the remaining renewable energy-using power plants, the MEET model fits to the same range as the two given scenarios.

Besides a general spread of the energy supply models the comparison (tab.: 4.1 to 4.7) showed that the main deviation to the MEET model occurred in the gas, coal and nuclear power plants and the CSP plants. A reason for the mismatches of the utilised CSP capacity might be the sensitivity on the solar multiple, which means that the ratio of solar field size and rated generator power can vary between the different energy models and therefore the behaviour of the CSP plants changes. Additionally the Leitstudie make use of some regions of North Africa as well for the electricity generation, where the potentials of CSP plants are even higher than in Europe.

Concerning the full load hours of all power plants, fig.: 4.6 (a) and (b) offer a summary for the seven observed scenarios, while each yellow bar in the figures represents the MEET model version of the in front standing corresponding energy supply scenario being colour-coded.

The gas, coal and nuclear power plants in sum fit well to the electricity generation of the other scenarios but as individuals the MEET model tends to use the nuclear and coal power plants too often while reducing the use of gas power plants. This is based on the different boundary conditions for the use of these power plants by the energy models. While the MEET model simply follows the order of using nuclear, coal followed by the gas power plants, the other models are tuned towards today's power plant use. So the model used for the Energiestudie has to consider a minimum full load hours of each power plant which are set, for example, for gas power plants to 3066 h (Lanz et al., 2009). This automatically reduces the utilised capacity of the nuclear and coal power plants. The model for the Leitstudie does not even simulate gas, coal and nuclear power plants explicit, but calculates the needed capacities for nuclear, coal and gas power from the annual load duration curve of the residual load of the simulation. So the nuclear power plants are defined for the capacity range with at least 7000 full load hours, coal power plants come with full load hours between 7000 h and 2000 h and the range below is set to gas power plants (Nitsch et al., 2010a). This way of tuning the models might help to get the use of the power plants closer to the behaviour of today, but these restrictions bias the simulation of future energy scenarios, where a change in the power plant mix could also require a change in the way of using the gas, coal and nuclear power plants.

In summary, this section showed the behaviour of the MEET model related to the very basics of the global distribution of renewable power potentials, over the representation of single power plants up to the simulation of whole energy supply scenarios, from conventional up to highly renewable. The MEET model performed quite well, specially for the power plants based on renewable energies, but also the gas, coal and nuclear work well considering that they are not specially tuned to todays use. So these comparisons help to arrange the results and their interpretations presented in the following sections.

Table 4.1.: Comparison of Europa27 reference 2009 scenario from Teske et al. (2012) with the MEET model. The 'capacity factor' indicates the ratio of installed power plant capacity and annual mean required electric power. The 'power' column shows the scenario settings as the power plant mix in percent of the total power plant capacity. The columns 'gen. el.' and 'load' represent the model outputs to compare in terms of the percentage fraction of electricity generation per power plant type and the utilised capacity of the power plant types as full load hours.

Model		Original		MEET		MEET adapted	
Capacity factor		2.38		1.7		2.38	
Power plant	Power [%]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]
Coal	19	23.55	4468	27.15	7358	22.1	4292
Gas	24	19.56	2978	16.3	3504	9.38	1402
Nuclear	21	35.32	6220	35.37	8672	40.29	7096
Bio / Geo	2	2.81	5957	3.41	8760	3.47	6395
Hydro	21	12.96	2278	10.73	2628	15.02	2628
Wind onshore	11	5.25	1752	6.59	3066	9.1	3066
PV	2	0.55	964	0.45	1139	0.63	1139

Table 4.2.: Comparison of Europa27 reference 2050 scenario from Teske et al. (2012) with the MEET model. For explanation of nomenclature see tab. 4.1.

Model		Original		MEET		MEET adapted	
Capacity factor		2.78		2.40		2.78	
Power plant	Power [%]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]
Coal	10	12.46	4117	19.71	7096	18.6	5869
Gas	21	22.13	3329	17.67	3066	13.69	2015
Nuclear	8	19	7096	17.57	7972	16.69	6658
Bio / Geo	2	4.74	6833	3.48	6307	3.47	5431
Hydro	15	11.22	2365	10.9	2628	12.52	2628
Wind onshore	22	16.04	2278	17.56	2891	19.88	2803
Wind offshore	5	6.03	3854	6.42	4643	7.3	4555
PV	15	6	1314	4.77	1139	5.47	1139
CSP	1	0.77	4468	1.09	3942	1.25	3942
Wave / Ocean	1	1.61	3504	0.84	3066	0.96	3066

Table 4.3.: Comparison of Europa27 [r]evolutuion 2050 scenario from Teske et al. (2012) with the MEET model. For explanation of nomenclature see tab. 4.1.

Model		Original		MEET	
Capacity factor		3.73		3.87	
Power plant	Power [%]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]
Gas	2	0.9	876	2.87	3241
Bio / Geo	2	6.4	6482	3.49	3942
Hydro	12	11.6	2365	13.95	2628
Wind onshore	22	21.15	2278	26.23	2716
Wind offshore	13	21.24	3767	22.72	3942
PV	40	21.91	1314	19.91	1139
CSP	6	12.2	4993	7.08	2628
Wave / Ocean	3	4.6	3504	3.75	2803

Table 4.4.: Comparison of Energiestudie 2007 scenario from Lanz et al. (2009) with the MEET model. For explanation of nomenclature see tab. 4.1.

Model		Original		MEET		MEET adapted	
Capacity factor		1.92		1.56		1.92	
Power plant	Power [%]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]
Coal	38	48.93	5782	49.65	7358	45.96	5519
Gas	21	14.17	3154	10.91	2891	7.25	1577
Nuclear	16	23.23	6570	24.77	8760	29.28	8410
Bio / Geo	2	3.13	5869	3.12	8760	3.47	7884
Hydro	3	3.46	5256	1.41	2628	1.73	2628
Wind onshore	17	6.59	1840	9.51	3154	11.53	3066
PV	3	0.49	788	0.63	1139	0.77	1139

Table 4.5.: Comparison of Energiestudie 2020 scenario from Lanz et al. (2009) with the MEET model. For explanation of nomenclature see tab. 4.1.

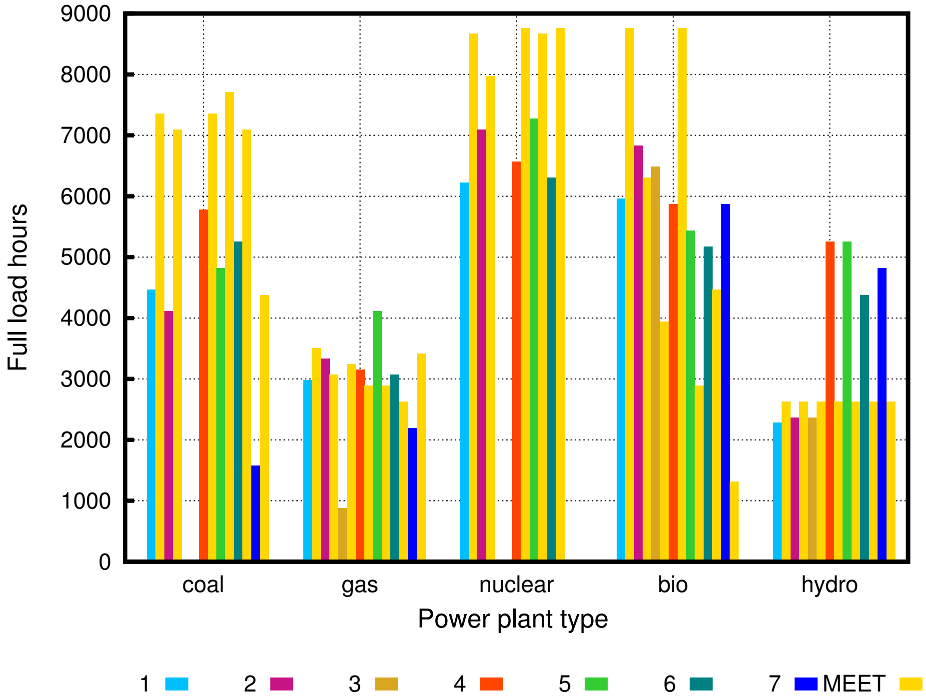
Model		Original		MEET		MEET adapted	
Capacity factor		2.26		2.08		2.26	
Power plant	Power [%]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]
Coal	28.38	35.19	4818	51.43	7709	51.71	7183
Gas	22.77	24.41	4117	15.58	2891	13.19	2190
Nuclear	2.7	5.05	7271	6.18	8672	6.57	8672
Bio / Geo	4.89	6.82	5431	3.47	2891	3.48	2716
Hydro	3.34	4.55	5256	1.88	2628	2.03	2628
Wind onshore	26.47	20.12	2978	18.45	2891	19.76	2803
PV	11.45	3.87	1314	3.02	1139	3.26	1139

Table 4.6.: Comparison of Leitstudie 2009 scenario from Nitsch et al. (2010a) with the MEET model. For explanation of nomenclature see tab. 4.1.

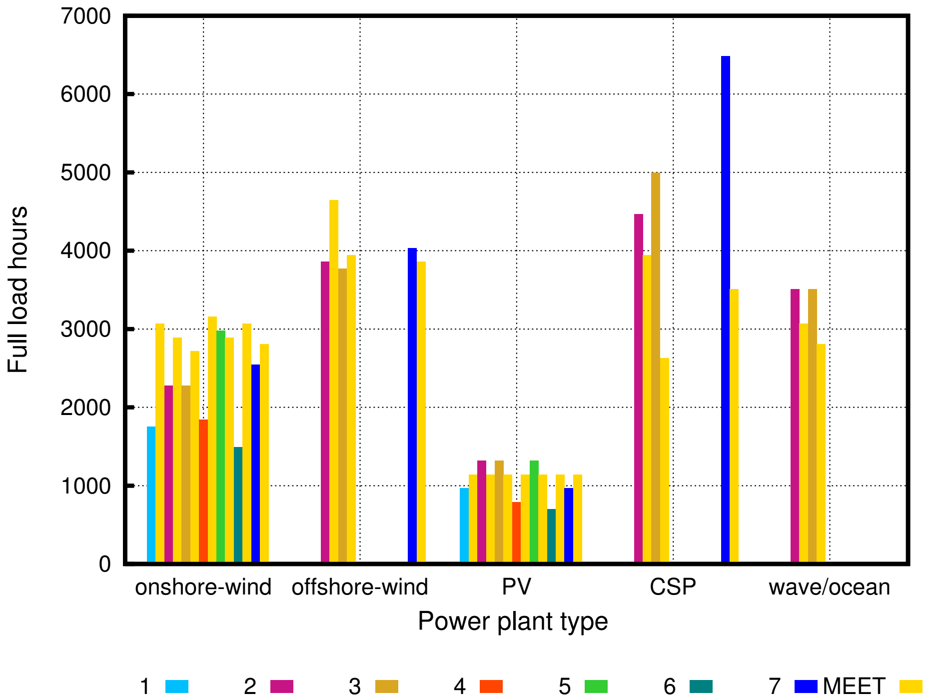
Model		Original		MEET		MEET adapted	
Capacity factor		2.18		1.69		2.18	
Power plant	Power [%]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]
Coal	36	47.23	5256	49.26	7096	43.32	4818
Gas	18	13.88	3066	9.06	2628	6.79	1489
Nuclear	15	22.86	6307	25.2	8760	29.99	8059
Bio / Geo	4	5.17	5168	3.47	4468	3.47	3504
Hydro	3	3.23	4380	1.52	2628	1.96	2628
Wind onshore	17	6.51	1489	9.93	3066	12.46	2978
PV	7	1.12	701	1.57	1139	2.01	1139

Table 4.7.: Comparison of Leitstudie 2050 scenario from Nitsch et al. (2010a) with the MEET model. For explanation of nomenclature see tab. 4.1.

Model		Original		MEET	
Capacity factor		3.19		3.41	
Power plant	Power [%]	Gen. el. [%]	Load [h]	Gen. el. [%]	Load [h]
Coal	4	2.53	1577	6.79	4380
Gas	14	10.96	2190	18.56	3416
Bio / Geo	7	14.26	5869	3.49	1314
Hydro	2	4.23	4818	2.05	2628
Wind onshore	19	17.06	2540	20.94	2803
Wind offshore	18	26.95	4030	26.8	3854
PV	30	10.32	964	13.25	1139
CSP	6	13.7	6482	8.12	3504



(a)



(b)

Figure 4.6.: Comparison of the use of the different power plant types by the different models in terms of full load hours of power plants for the investigated energy scenarios: 1 = Europa27 Referenz 2009, 2 = Europa27 Referenz 2050, 3 = revolution revolution 2050, 4 = Energiestudie 2007, 5 = Energiestudie 2020, 6 = Leitstudie 2009, 7 = Leitstudie 2050 and in yellow the corresponding MEET model result. (a) Weather independent power plants. Especially this power plant types show a wide range of the utilised capacity as the models use different approaches to define the way the plants are used. (b) Power plants using weather dependent renewable energies. In this case the largest differences occur for CSP plants as they vary in their setup of solar multiple and heat storage, having a large impact on the utilised capacity.

5. Electricity supply scenarios and MEET model results

The investigated electricity supply scenarios and the results of their simulation by the MEET model will be presented in this section and further discussions can be found in section 6. The focus is on the general behavior of the different electricity supply strategies with an high share of renewable energies and especially the requirements on energy storage options.

As wind power- and PV- plants are expected to dominate the future electricity supplies based on renewable energy (Heide et al., 2010), the influence of mixing wind and solar power on the thereby required energy storage capacity was investigated. Based on the resulting supply scenario in terms of minimum required energy storage capacities, the transition was investigated from todays power plant mix to the presented 100 % wind and PV scenario. Because the resulting needs for energy storage capacities turned out to be quite high, additional options to minimize their need were analysed. So the option of adding excess power plant capacities and variations in the power plant mix and power plant management strategies will be presented in this section together with their influence on the requirements of energy storage.

Not only the fluctuation of the electricity supply based on weather dependent renewable energy sources during a particular year, but also their variation in multiple years, are important points to investigate. Therefore weather data of the years from 2000 to 2010 were implemented to the MEET model to show the variation of the results of electricity supply. In order to save computation time, the spread of the different years has not be taken into account for all scenarios investigated. Instead, the focus was on the representative year 2009 in order to obtain comparable results.

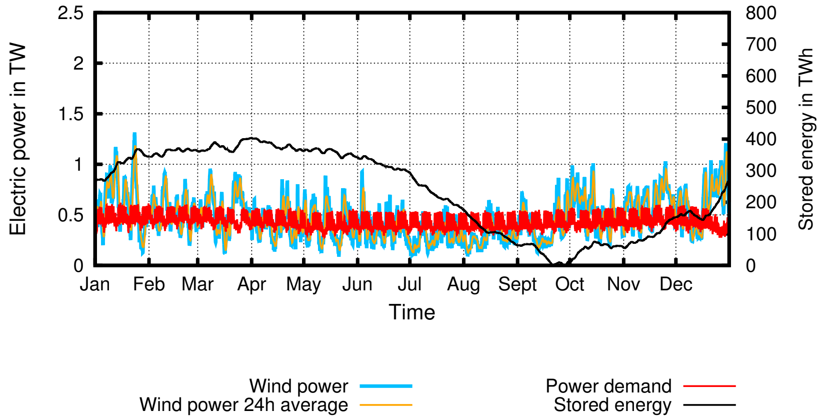
5.1. Mixing solar and wind power to reduce the required energy storage capacity

A critical point of wind and solar power is their temporal variability. So there is no guaranty that electricity can be generated exactly on demand. To allow a shifting of the solar and wind power to the time when the electricity is needed, energy storage options or controllable backup power plants are required.

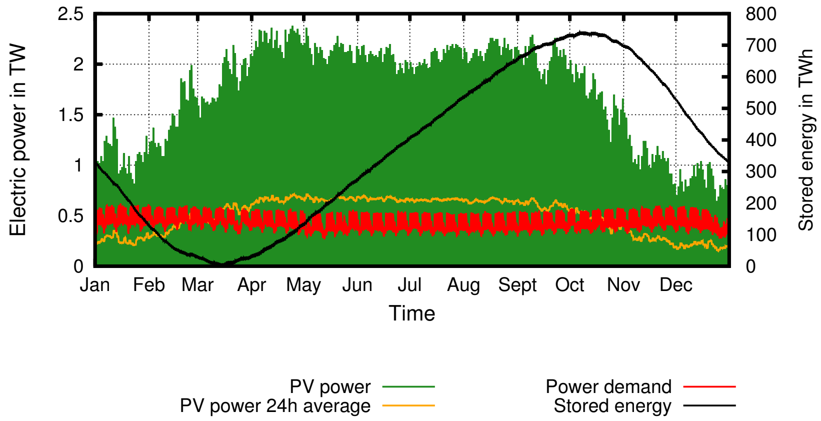
5.1.1. The seasonal cycle of wind and solar power at the example of Europe

Looking for the annual behavior of wind and solar power particularly at the west wind zones, where the variation tends to be large due to low-pressure systems and seasonal changes, the idea of combining these two power sources becomes obvious. So, for example, for the MEET model region of Europe with an annual electricity demand of 3956 TWh (see tab.: 3.3 for all model regions) and the weather data of 2009, an electricity supply scenario based on 100 % wind power leads to a much too high generated electric power during the winter half-year with peaks up to three times larger than the power demand of about 0.45 TW on the annual average. But the summertime half-year is dominated by a deficit in electricity generation (fig.: 5.1 (a)). So, to get electricity generation and demand together, a huge energy storage with a capacity of about 400 TWh or 10 % of the annual electricity demand would be needed. In autumn the storred energy effectively rises till late spring time and is used for electricity generation over the sumer season. For a 100 % PV based supply scenario, electricity generation is moved by half a year. In this case, most electricity is generated during the summer season with a generated power up to four times higher than required in this time. But for the winter season the electricity generation is reduced by more than a half. Regarding the fig.: 5.1 (b) it has to be acknowledged that of course the PV will not generate electricity during night time, but the resolution of the one year plot is not good enough to identify the daily variation explicitely and thereby looks more like a filled curve. Therefore the 24 hours averaged PV electricity generation has been plotted as well. The use of the energy storage is as well shifted by half a year compared to the wind power scenario. So the stored energy rises during summer on the long run up to about 740 TWh (18.7 % of the annual electricity demand of the region) and get used during the winter season.

The above shown shift in electricity generation by wind and PV power forces a mixing of these two major electricity generation technologies to reduce the required energy storage capacity. In the case of Europe it will be shown later that a mix of 30 % wind power and 70 % PV power installed capacity leads on average to a minimum of required storage capacity (fig.: 5.2 (a)). In the case of the weather conditions of 2009 the needs for an energy storage to balance the seasons are reduced to a capacity of 150 TWh or 3.8 % of the annual electricity demand. The stored energy now reaches the maximum in the begining of the summer and due to the still high ratio of PV power with its daly cycle, the maximum generated electric power still tops the demand by a factor of three, but the 24 hours average gets quite close to the demand curve (fig.: 5.1 (c)).



(a)



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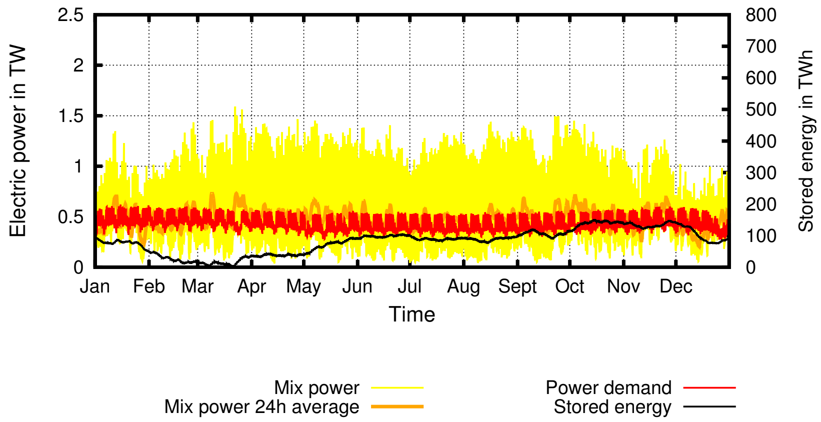


(c)

Figure 5.1.: Comparison of Europe electricity supply by wind and PV power calculated with MEET for weather data of 2009 and an annual demand of 3956 TWh. Hourly electric power and demand (red line) on left axis and stored energy on right axis. (a) 100 % wind power scenario with highes power feed in at winter and a deficit during summer. (b) 100 % PV power scenario showing the highest required energy storage capacity and electric power feed in, which is required to compensate the night time. (c) 30 % wind 70 % PV installed power scenario requiering the smallest energy storage as wind and PV power complement well.

5.1.2. The influence of installed wind and PV power ratio on the required energy storage

To investigate on the dependencies of the requirements for energy storage on an electricity supply by using only PV and wind power, varying scenarios from 100 % wind to 100 % PV have been simulated. The mix of installed power has been changed in 10 % steps for all model regions of the MEET model and, where simulated, for all years of weather data from 2000 to 2010 to see the annual variety as well. Regarding the energy storage needs with dependency on the mix of PV and wind power, PV power seems to play an important role for most regions to reduce the storage needs (compare fig.: 5.2, 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8).

In the case of Europe (fig.: 5.2(a)) the on-average minimum needed energy storage capacity of 3.8 % with a standard deviation of $\pm$ 1 % of the annual electricity demand occurs at a mix of 30 % wind power and 70 % PV power for the weather data for 2000 to 2010. From this power plant ratio, it rises quite fast for higher ratios of wind power up to 13.3 % $\pm$ 2 % and for an enlarged ratio of PV power up to even 17.7 % $\pm$ 0.7 % of the annual electricity demand. The quite high variability of the storage needs for the observed eleven years given by the standard deviation shows that the needed storage capacity that could be expected in the worst case year could be up to two percentage points higher. Otherwise, the large variability even allows the total minimum required energy storage to shift to a power mix of 40 % wind and 60 % PV (fig.: 5.2(a)) for the weather of 2009. The standard deviation itself is highest for the 100 % wind power scenario and declines with rising PV power ratio, which fits in well to the potentials and their variability given in fig.: 4.3 (a) and (b) and fig.: 4.2 (a) and (b).

The behaviour of the required energy storage capacity, depending on the mix of installed wind and PV power presented in fig.: 5.2 (a) has been calculated by the MEET model in 10 % steps of power capacity mixing ratios. To get a function describing this behaviour for any mixing ratios a function can be fitted to this data. This fit function will be needed in section 6.2.5 and 6.3 to establish an equation describing the required energy storage capacity and the cost of electricity for any wind and PV power scenario. In this case a polynomial fit in the way of

$$y(x) = a + b \cdot x + c \cdot x^2 + \dots \qquad [5.1]$$

(red line in fig.: 5.2 (a)) with $x \in [1, 11]$ was used. To translate x into the ratio of wind and PV power, one can use $x = \left(1 + \frac{\mu}{10}\right)$ with $\mu \in [0, 100]$ as percentage of installed PV power. The order of the polynomial (eq.: [5.1]) used for the fit depends on which order is required to get a good match to the data. In the case of Europe (fig.: 5.2(a)) a polynomial of the order of four leads to the parameters $a = 15.224$, $b = -2.537$, $c = 0.728$, $d = -0.154$ and $e = 0.010$.

At the point of the storage capacity optimized wind and solar power ratio, the generated electricity per plant type came out as 49.6 % of the annual electricity demand generated by wind power and 56.1 % by PV. The 5.7 % of annual demand in addition generated electricity, belongs to the losses of charging and discharging the energy storage during the year. This extra generation to compensate the looses vary by the power mix as well and starts with 4 % for wind power becoming higher with rising PV ratio up to 11.3 % (fig.: 5.2(b)) as the need for the energy storage is more frequent than wind power simply to compensate the night time.

Regarding the total amount of power plant capacity, the energy storage capacity optimised scenario is not the lowest by far (fig.: 5.2(c)). This is based on the fact that the degree of capacity utilisation of wind power plants is typically higher than those of PV power plants. In the case of Europe, wind power comes with full load hours in the order of 2100 h and PV power with 1050 h in the MEET model. Mainly driven by this, the required power plants, to meet electricity demand start at 491.1 % $\pm$ 23.3 % of annual mean required power for the 100 % wind power scenario and rises up to 998 % $\pm$ 10.9 % for the 100 % PV power scenario (fig.: 5.2(c)). The growth rate of power plant capacity needed to be installed for a rising ratio of PV power can well be described by an exponential growth in the way of

$$y(x) = \tilde{a} + \tilde{b} \cdot e^{x \cdot \tilde{c}} \qquad [5.2]$$

with $x \in [1, 11]$. Again the fit function will be used together with the fit of eq.: [5.1]in section 6.2.5 and 6.3. Fitting eq.: [5.2] to the data of fig.: 5.2(c) determines the parameters to $\tilde{a} = 487.774$, $\tilde{b} = 9.816$ and $\tilde{c} = 0.356$.

Considering the fast rise of power plant capacities for an increase of PV power it should be mentioned that in this physical consideration, the power mix requiring the lowest energy storage capacities is seen as the most favourable, as the potential of wind and PV power are not that limited as the options to store energy in the amount of some percent of the annual electricity demand. For further discussion and the change in favourable power mix depending on energy storage cost see section 6.3.

In the case of Australia (fig.: 5.3(a)) and South America (fig.: 5.4(a)) the situation for the power plant mix concerning the minimization of energy storage needs is much the same as for Europe. But now, on average, the minimum capacity is reached for 50 % wind power and 50 % PV power with a demand for storage capacity of 4.9 % $\pm$ 1 % of the annual electricity demand for Australia and 4.3 % $\pm$ 0.8 % for South America. The behaviour for South America looks quite familiar with a higher demand for energy storage capacities for the PV scenario compared to the wind scenario, and a mainly rising standard deviation for a rising ratio of wind power. In contrast, Australia shows a maximum in the required storage capacity for having 20 % wind power and 80 % PV power installed. Also the size of the standard deviation of the supply scenarios do not depend on the wind power for the Australian model region. The fit of a polinomial of the order of five to the data of Australia leads to the parameters $a = 6.93$, $b = -0.069$, $c = -0.037$, $d = -0.035$, $e = 0.008$ and $f = -0.0004$ and to describe the behaviour for South America a polinomial of the order of four leads to the parameters $a = 5.241$, $b = 0.155$, $c = -0.128$, $d = 0.01$ and $e = 0.0004$.

From the point of view of the share of generated electricity by wind and PV power, the storage capacity is not optimal for an equal share as for Europe. Now electricity generated by wind power is dominating with 72 % of annual needed electic energy for Australia (fig.: 5.3(b)) and 76 % for South America (fig.: 5.4(b)). Also the slope for the growth rate of electric energy generated by wind power depending on the rising ratio of wind power is not that linear as for Europe, it is better described as a restricted growth.

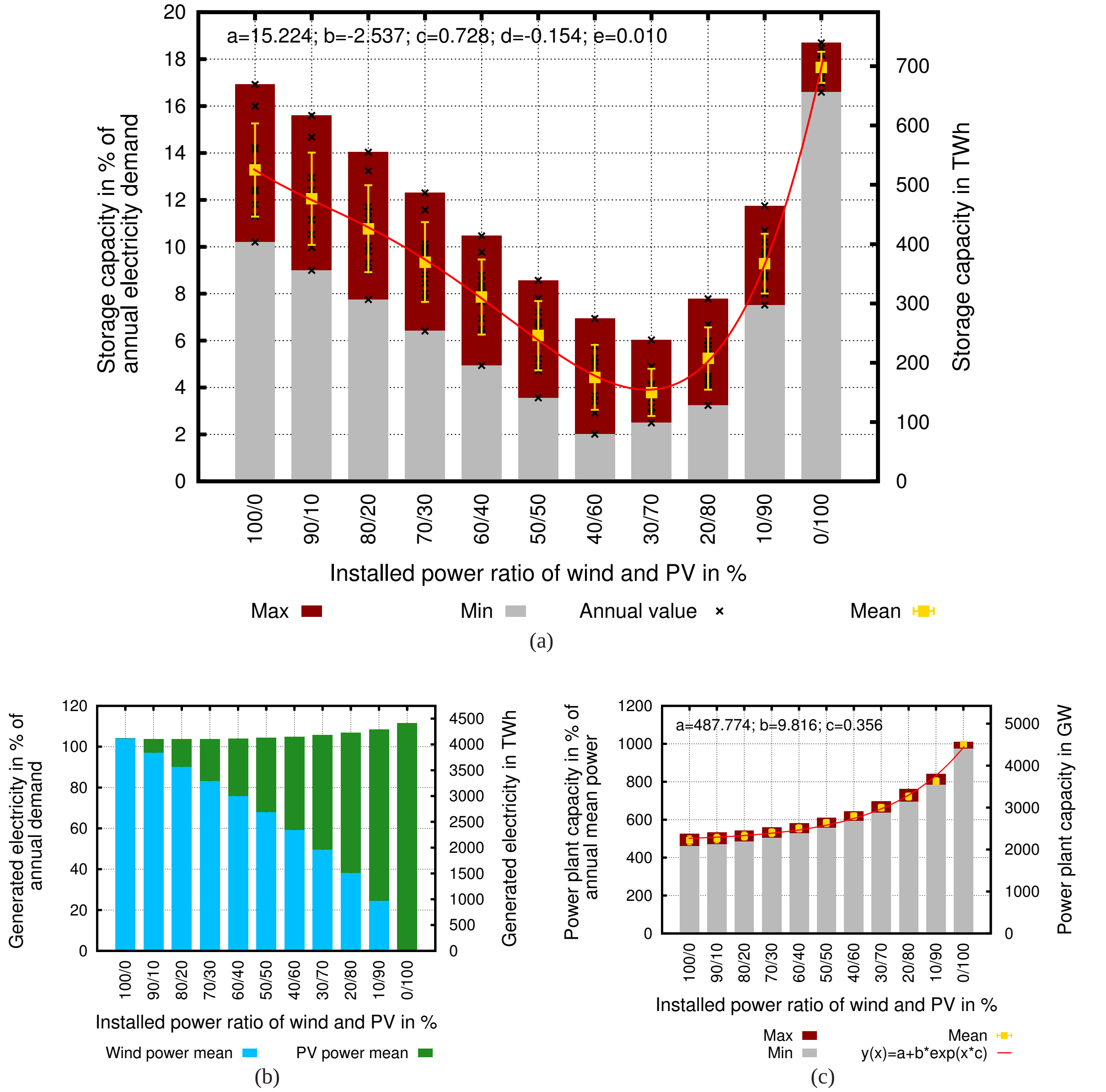


Figure 5.2.: Electricity supply of Europe (3956 TWh/a) for varying ratios of installed wind and PV power starting at the left with 100 % wind and 0 % PV power and going by 10 % steps to a 0 % wind and 100 % PV power scenario calculated by using weather data from 2000 to 2010. (a) Required energy storage capacity, while 1 % storage capacity of annual electricity demand is eqivalent to 87.6 h of mean electricity supply: red bar indicating the maximum required energy storage capacity of the eleven simulated years, gray bar the minimum required energy storage capacity, black cross the annual values of required energy storage capacity at the individual years, yellow mark for the mean required energy storage capacity with error bars for the one sigma range and red line as fit of eq.: [5.1] with fit parameters in plot. (b) The amount of electricity generated by wind and PV power. (c) The required power plant capacity to be installed for the supply scenarios: red bar indicating the maximum required power plant capacity of the eleven simulated years, gray bar the minimum required power plant capacity, yellow mark the mean required power plant capacity with error bars for the one sigma range and red line as fit of eq.: [5.2] with fit parameters in plot.

As for all model regions, the required power plant capacity rises strongly for high ratios of PV power. So Australia starts with an required power plant capacity of 342.3 % ± 17.4 % of the mean annual electricity demand and ends at 813.3 % ± 5.2 % (fig.: 5.3(c)). The required power plant capacity of South America reaches from 246.8 % ± 20.5 % to 735.9 % ± 3.3 % of the mean annual electricity demand (fig.: 5.4(c)). Fitting eq.: [5.2] to the data results in the parameters $\tilde{a} = 287.955$, $\tilde{b} = 47.89$ and $\tilde{c} = 0.217$ for Austarlia and $\tilde{a} = 236.584$, $\tilde{b} = 15.404$ and $\tilde{c} = 0.314$ for South America.

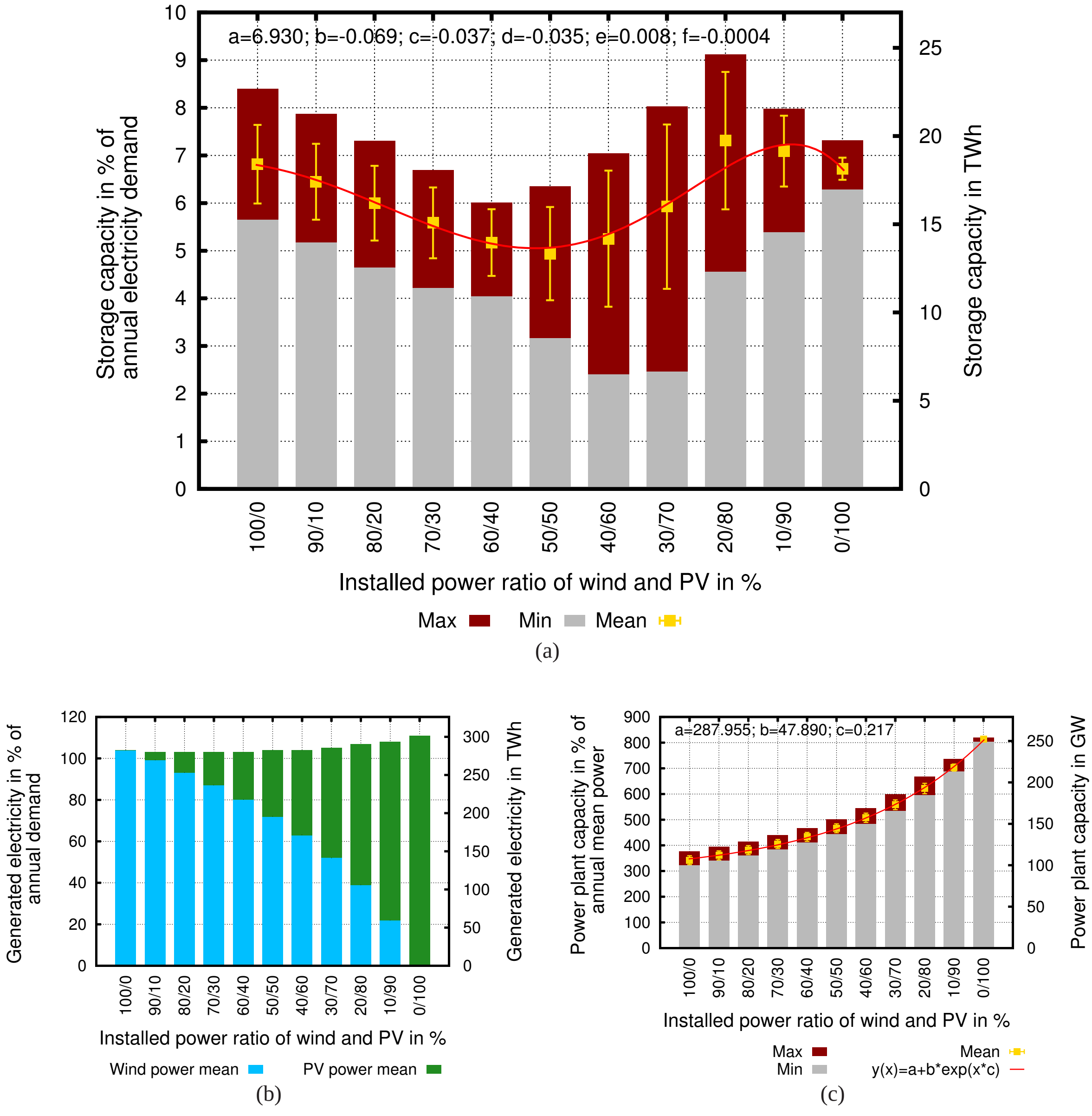
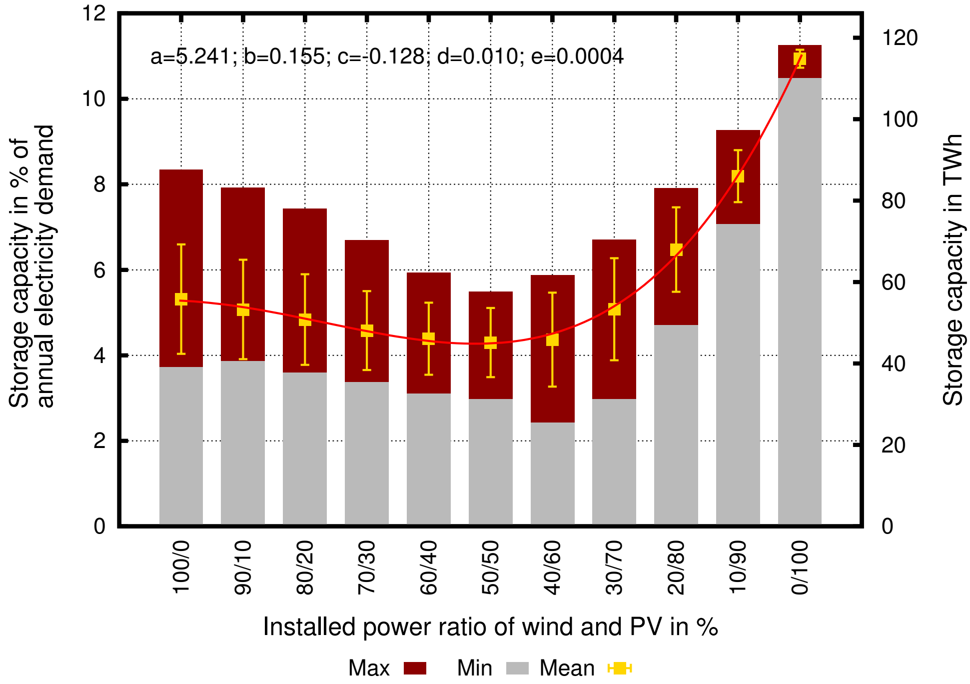


Figure 5.3.: As fig.: 5.2 but for Australia with an electricity demand of 272 TWh/a.

For North America and New Zealand, the minimum required energy storage capacity has moved to a power plant ratio of only 10 % wind power but 90 % PV power (fig.: 5.5(a) and 5.6(a)). In both cases the storage capacity does not rise much from its 2.2 % ± 0.3 % of annual electricity demand for



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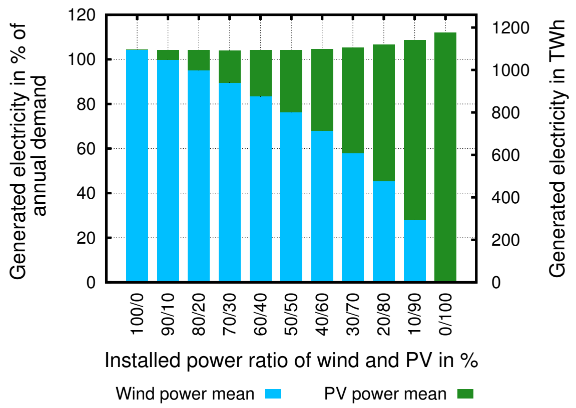

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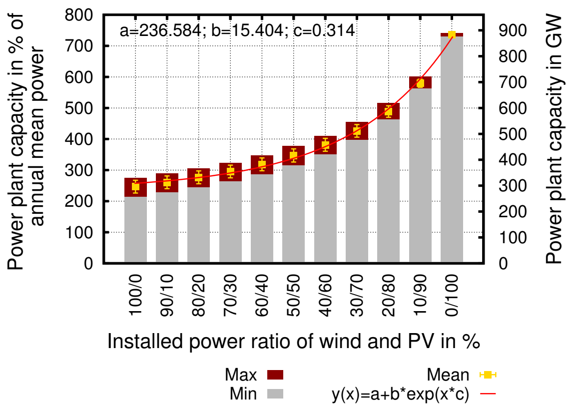


(c)

Figure 5.4.: As fig.: 5.2 but for South America with an electricity demand of 1050 TWh/a.

North America or its 5.4 % ± 0.8 % for New Zealand, but for the 100 % wind power scenario, the required capacity rises up to 8.2 % ± 0.9 % respectively 11.4 % ± 2.6 % of the annual electricity demand. Fitting a polinomial of the order of six to the results for North America gives the parameters $a = 11.783$, $b = -6.578$, $c = 4.125$, $d = -1.294$, $e = 0.204$, $f = -0.016$ and $g = 0.0005$ and for New Zealand a polinomial of the order of five leads to the fit parameters $a = 11.204$, $b = 0.728$, $c = -0.741$, $d = 0.16$, $e = -0.016$ and $f = 0.001$.

With regard to the share of electricity generated by wind and PV power at the minimum of required energy storage capacity, wind power generates only 23.8 % of the annual electricity demand for North America or 20.9 % for New Zealand (fig.: 5.5 (b) and 5.6 (b)).

The required amount of installed power plant capacity for the electricity supply of the scenarios increases with the ratio of PV power from 373.7 % ± 8.2 % of the mean annual electricity demand to 814.9 % ± 5.1 % coupled with a reduction of the standard deviation for North America (fig.: 5.5 (c)). For New Zealand it is the same behaviour starting with an power plant capacity of 404.9 % ± 38.3 % of the mean annual electricity demand and ending at 873.9 % ± 9.2 % (fig.: 5.6 (c)). Fitting eq.: [5.2] on the data of North America delivers the parameters $\tilde{a} = 357.001$, $\tilde{b} = 19.055$ and $\tilde{c} = 0.287$ and for New Zealand $\tilde{a} = 339.793$, $\tilde{b} = 58.044$ and $\tilde{c} = 0.201$.

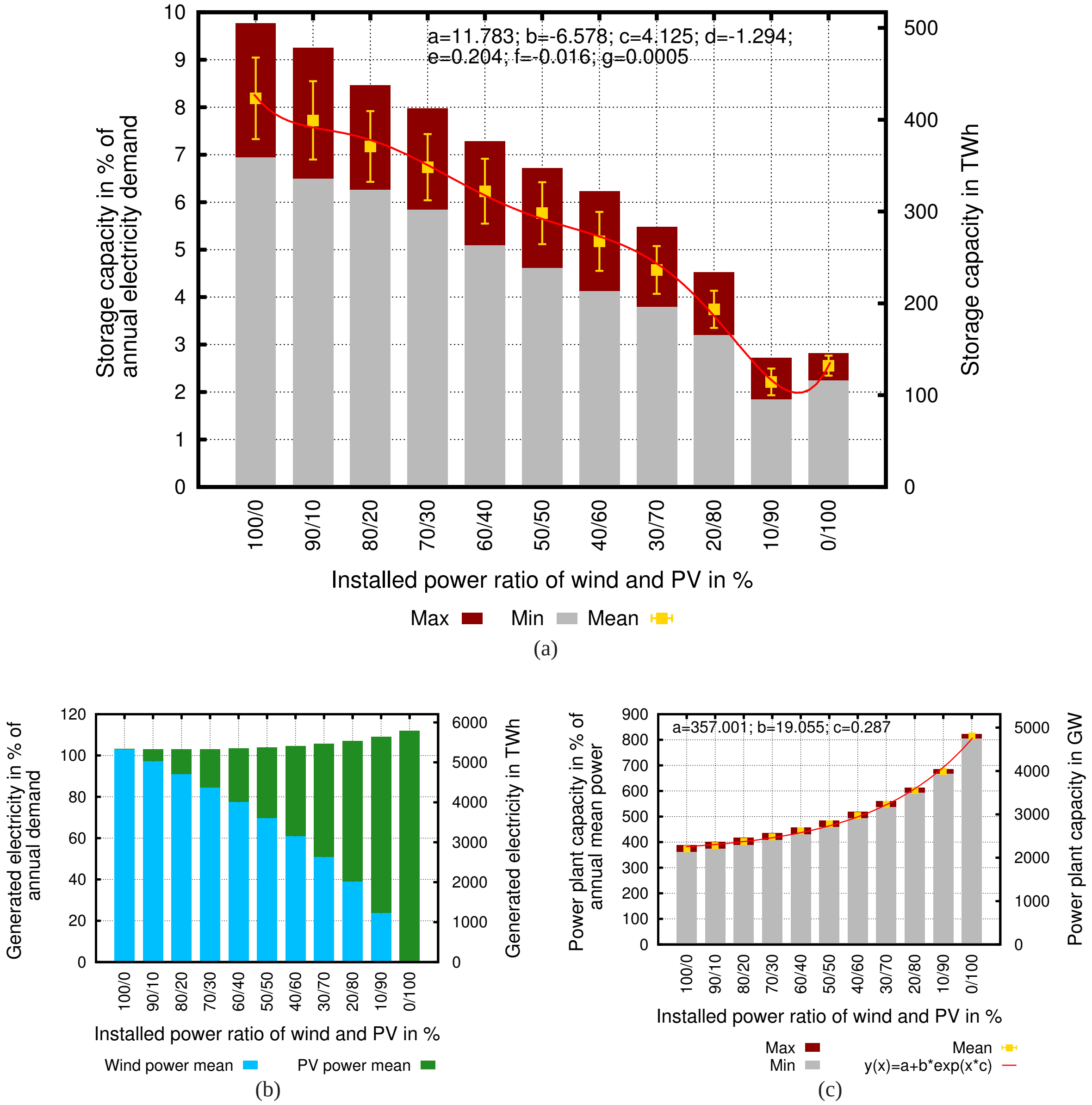


Figure 5.5.: As fig.: 5.2 but for North America with an electricity demand of 5172 TWh/a.

The extreme cases occur for the model regions Asia and Africa, where the lowest demand for energy storage capacities of 1.9 % ± 0.2 % of annual electricity demand for Asia or 5.6 % ± 0.2 % for Africa

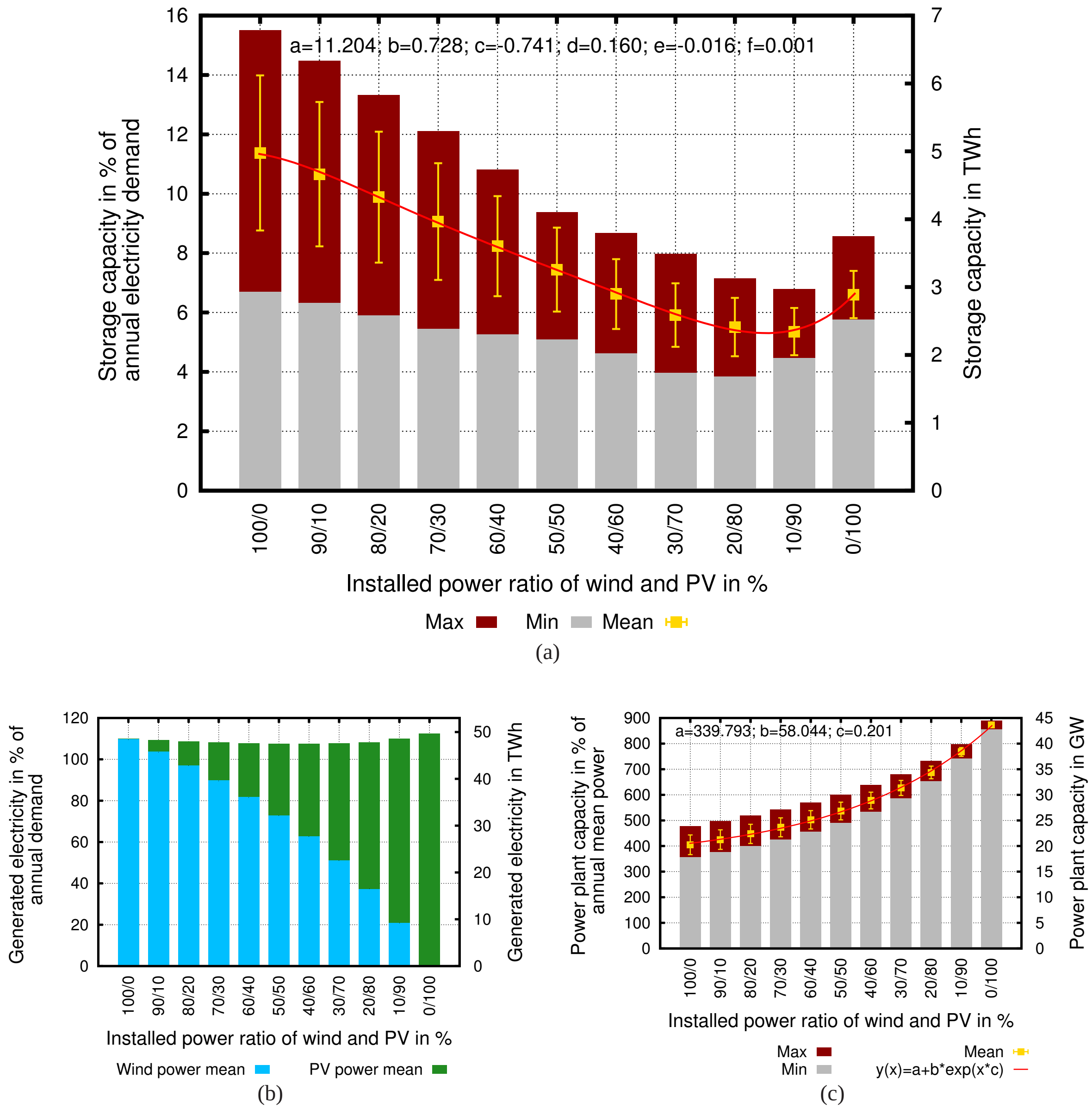


Figure 5.6.: As fig.: 5.2 but for New Zealand with an electricity demand of 44 TWh/a.

is reached by the 100 % PV power supply scenario (fig.: 5.7(a) and 5.8(a)). Quite special as well is the strong reduction of storage needs at the end for high ratio of PV power, while the first reduction of wind power by up to 50 % has by far not such a high impact. The given behaviours can be represented in the way of eq.: [5.1] as a polinomial of the order of four with the fit parameters $a = 10.76$, $b = -1.67$, $c = 0.46$, $d = -0.057$ and $e = 0.002$ for the region of Asia and using a polinomial of the order of six with $a = 29.051$, $b = -3.285$, $c = 1.18$, $d = -0.772$, $e = 0.154$, $f = -0.014$ and $g = 0.0005$ for Africa.

Regarding the share of generated electricity, generation by wind power rises almost constant with wind power capacity for Asia, while for Africa it is a restricted growth (fig.: 5.7(b) and 5.8(b)).

The increase of required power plant capacity towards a high ratio of PV power is comparatively small for Asia. It changes from 517.6 % ± 22.6 % of the mean annual electricity demand for the wind only scenario to 749.7 % ± 3.7 % for the PV-only scenario with the special point that the first 20 % of PV power even reduces the in total needed power plant capacity by 7 % of the mean annual electricity demand (fig.: 5.7(c)). For Africa the behaviour of needed power capacity is quite typical and rises from 381.9 % ± 19 % of the mean annual electricity demand to 790.4 % ± 4.5 % in the 100 % PV scenario (fig.: 5.8(c)). Doing the fit of eq.: [5.2] to the required power plant capacities of Asia leads to the parameters $\tilde{a} = 500.146$, $\tilde{b} = 5.198$ and $\tilde{c} = 0.352$ and for Africa to $\tilde{a} = 350.817$, $\tilde{b} = 29.564$ and $\tilde{c} = 0.244$.

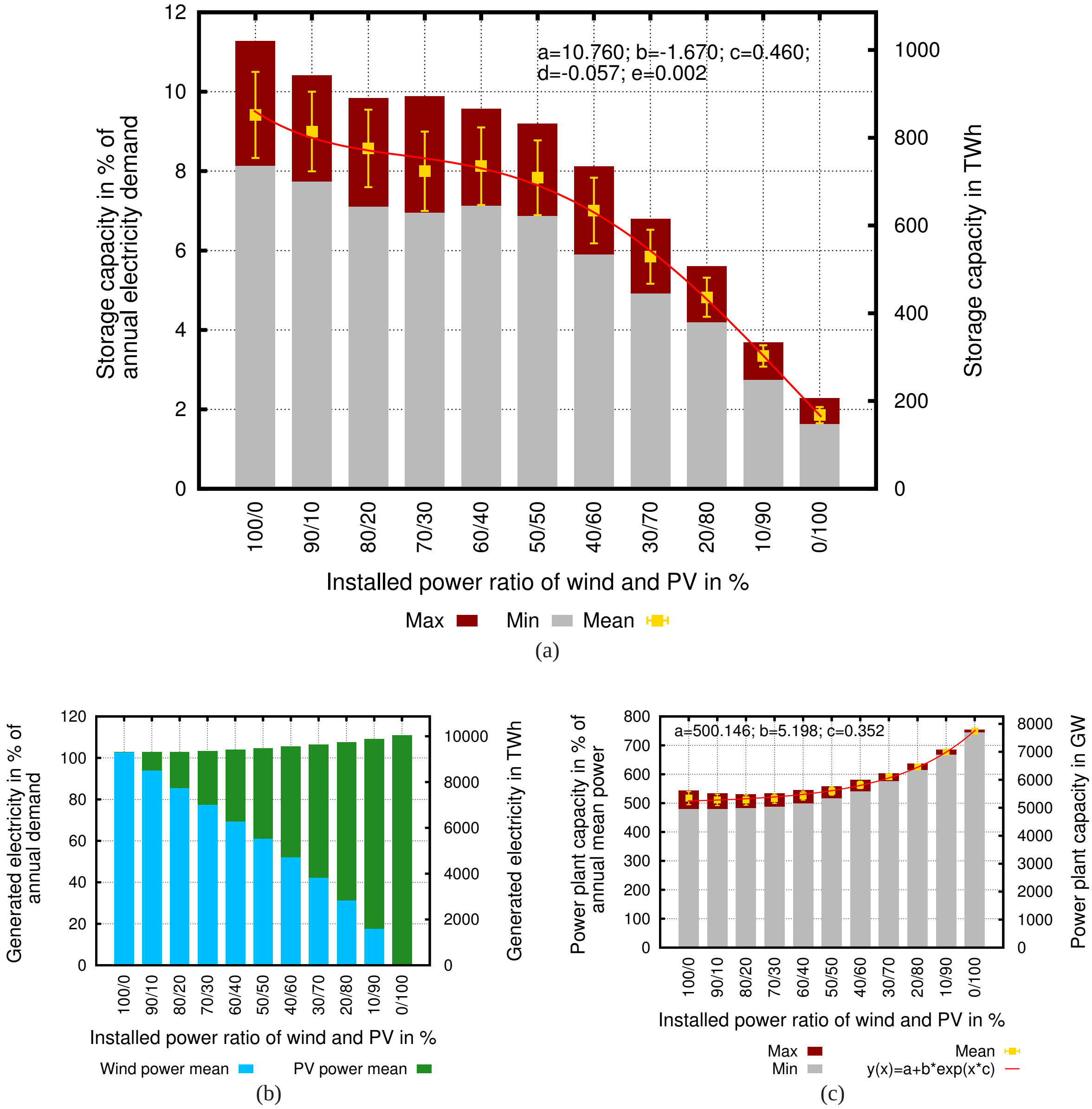


Figure 5.7.: As fig.: 5.2 but for Asia with an electricity demand of 9053 TWh/a.

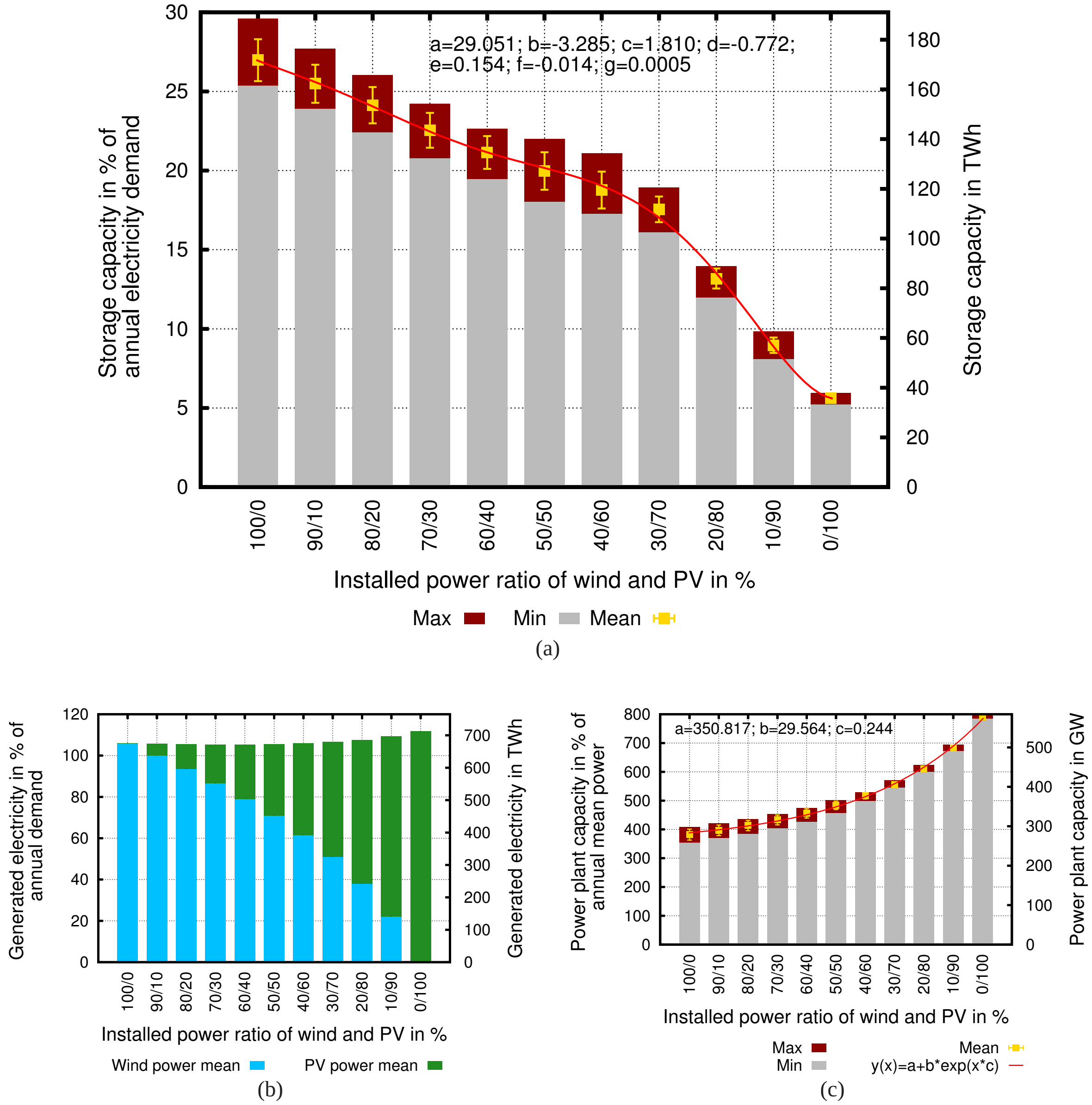


Figure 5.8.: As fig.: 5.2 but for Africa with an electricity demand of 638 TWh/a.

Finally, even if the different weather conditions of the MEET model regions lead to a specific mix of wind and PV power plants for a minimum on required energy storage capacities at the regions, in all cases the power plant capacity that needs to be installed rises with the ratio of PV power.

5.2. Reducing the required energy storage by adding excess power plant capacity

An electricity supply based on wind and PV power plants requires a large energy storage capacity to compensate the volatile electricity generation (section 5.1 and 5.4). In the case of Europe, at the optimal power plant mix to reduce the required energy storage capacity for a 100 % renewable electricity supply was found for 30 % wind and 70 % PV power plant capacity. This mix requires a storage capacity of 3.8 % (150 TWh) of the annual electricity demand (fig.: 5.2 (a)). Because even at this optimum the required energy storage capacity is significant high, it could be quite interesting to further reduce this high demand for energy storage capacities.

In this section the reduction of required energy storage capacity at a 100 % renewable wind an PV power based scenario is done by increasing the installed power plant capacities and has been simulated for all model regions with the weather data of the years 2000 to 2010. This increase of the installed power plant capacity is called in the following ’excess capacity’. The excess capacity represents the additional power plant capacity installed to the minimum required power plant capacity for electricity supply without excess capacity. It allows more electricity to be generated in times where originally the energy storeage was needed to compensate for the deficite in supply. Of course the additional power plants also generate electricity at times, when it is not required. So this excess electricity is wasted or might be used for something else.

To start at the lowest storage demand, for each individual region of the MEET model the mix of wind and PV power has been chosen that came out best in section 5.1. In the case of Europe the electricity supply is done by a mix of 30 % wind and 70 % PV power capacity. Installing additional power plant capacities to the number of required power plants in terms of excess capacity, leads to a strong decrease of the storage capacities (fig.: 5.9) needed to balance electricity generation and demand. The error bars in fig.: 5.9 correspond to the standard deviation of the mean storege capacity requirement resulting from the simulations using the weather data for the years 2000 to 2010.

Already an excess capacity of 10 % reduces the required energy storage capacity by more than a half, which is a comparable result to Heide et al. (2011). Coming to larger excess capacities, the decline of the required energy storage is continously reduced in an exponential decrease as described by

$$y(x) = a^* + b^* \cdot e^{-x \cdot c^*} \qquad [5.3]$$

with $x \in [0, 100]$. Fitting eq.: [5.3] on the data for Europe (red line in fig.: 5.9) while keeping the start and end value fixed, leads to the parameter $a^* = 0.193$, $b^* = 3.6$ and $c^* = 0.0944$. So the required energy storage converges to a minimum required level of 0.19 % (7.5 TWh) of the annual electricity demand for Europe. Only at the 20 % excess capacity and particularly at the 50 %, the fit function clearly underestimates the simulated storage requirements and the behaviour of the reduction effect is not exactly exponential for high excess capacities. The results of fitting eq.: [5.3] to the data given in fig.: 5.9 will be needed together with the results in section 5.1 to establish an equation describing the required energy storage capacity and the cost of electricity for any wind and PV power scenario in section 6.2.5 and 6.3.

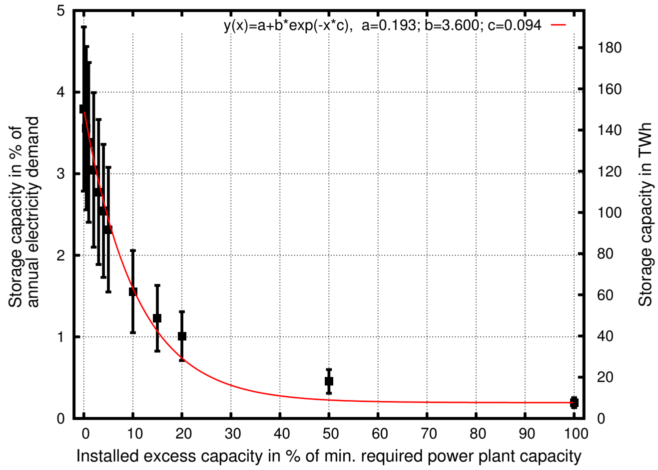


Figure 5.9.: Required energy storage capacity for installed excess power plant capacity from 0 % to 100 % of the minimum required power plant capacity in Europe for the 30 % wind and 70 % PV power scenario. Black dots for the mean required energy storage capacity calculated with the MEET model for the weather data from 2000 to 2010 and error bar for the one sigma standard deviation. The red line is the fit result of eq.: [5.3] and the fit parameter are written in the plot. For an electricity demand of 3956 TWh/a, Europe requires an energy storage capacity of 3.8 % (150 TWh) of the annual electricity demand (1 % is equivalent to 87.6 h of mean electricity demand) without excess power installed and with an exponential decline it ends at 0.2 % (8 TWh) of the annual electricity demand for 100 % excess capacity (a doubling of the power plant capacity).

In the case of Australia with its 50 % wind and 50 % PV power plant mix, the reduction of required energy storage capacity increases even faster. The standard devialtion also decreases continuously (fig.: 5.10). Just in the case of the 50 % excess capacity value, the fit of eq.: [5.3] with the resulting parameters $a^* = 0.151$, $b^* = 4.787$ and $c^* = 0.105$ does not describe the reduction in the correct way while underestimating the required energy storage capacity. Thus, the minimum required energy storage capacity converges to 0.15 % (0.4 TWh) of the annual needed electricity.

For the model region of South America, the decrease of required energy storage capacity for the power supply by 50 % wind and 50 % PV as well, is not as strong as for Australia. A reduction by a half appears here between 10 % and 15 % excess capacity and the standard deviation remains high (fig.: 5.11). Again, the storage capacity, at 50 % excess power capacity, is underestimated by the eponential decreas of eq.: [5.3] with the parameters $a^* = 0.288$, $b^* = 4.01$ and $c^* = 0.068$. The lowest energy storage capacity converges to 0.29 % (3 TWh) of the annual electricity demand for the region.

North America was simulated with a power plant mix of 10 % wind and 90 % PV for the lowest energy storage requirements. For this region the required energy storage capacities reduces very quickly and already an excess capacity of around 5 % reduces the energy storage by a half (fig.: 5.12). The standard deviation for the modeled years 2000 to 2010 is also quite small. The fit of eq.: [5.3] with the parameters $a^* = 0.151$, $b^* = 2.063$ and $c^* = 0.173$, represents the behaviour of the degression without any outliners. As minimum required energy storage capacity, it converges to 0.15 % (7.8 TWh) of the annual electricity demand of the region.

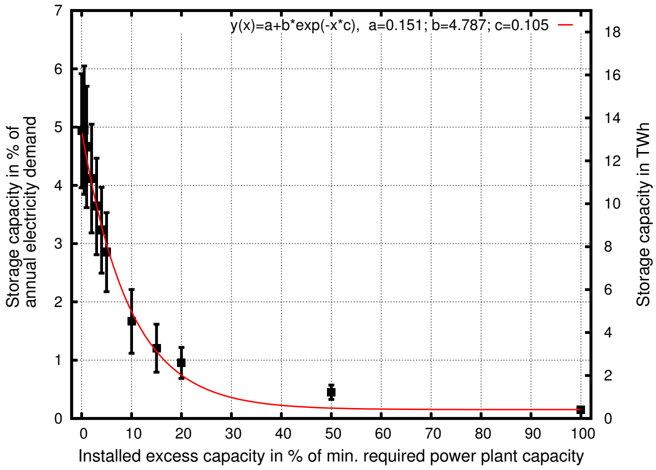


Figure 5.10.: Required energy storage capacity for installed excess power plant capacity from 0 % to 100 % of the minimum required power plant capacity in Australia for the 50 % wind and 50 % PV power scenario. Black dots for the mean required energy storage capacity calculated with the MEET model for the weather data from 2000 to 2010 and error bar for the one sigma standard deviation. The red line is the fit result of eq.: [5.3] and the fit parameter are written in the plot. For an electricity demand of 272 TWh/a, Australia requires an energy storage capacity of 4.9 % (13 TWh) of the annual electricity demand (1 % is equivalent to 87.6 h of mean electricity demand) without excess power installed and with an exponential decline it ends at 0.15 % (0.4 TWh) of the annual electricity demand for 100 % excess capacity (a doubling of the power plant capacity).

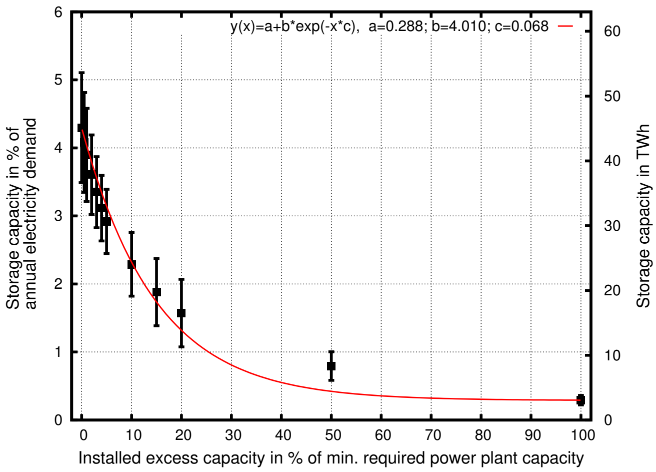


Figure 5.11.: Required energy storage capacity for installed excess power plant capacity from 0 % to 100 % of the minimum required power plant capacity in South America for the 50 % wind and 50 % PV power scenario. Black dots for the mean required energy storage capacity calculated with the MEET model for the weather data from 2000 to 2010 and error bar for the one sigma standard deviation. The red line is the fit result of eq.: [5.3] and the fit parameter are written in the plot. For an electricity demand of 1050 TWh/a, South America requires an energy storage capacity of 4.3 % (45 TWh) of the annual electricity demand (1 % is equivalent to 87.6 h of mean electricity demand) without excess power installed and with an exponential decline it ends at 0.3 % (3.2 TWh) of the annual electricity demand for 100 % excess capacity (a doubling of the power plant capacity).

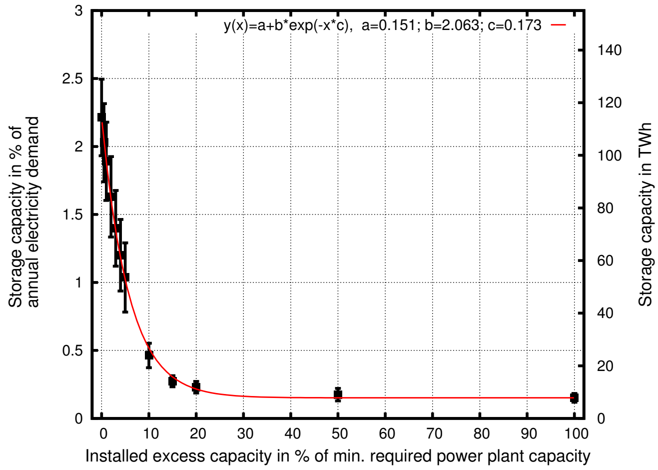


Figure 5.12.: Required energy storage capacity for installed excess power plant capacity from 0 % to 100 % of the minimum required power plant capacity in North America for the 10 % wind and 90 % PV power scenario. Black dots for the mean required energy storage capacity calculated with the MEET model for the weather data from 2000 to 2010 and error bar for the one sigma standard deviation. The red line is the fit result of eq.: [5.3] and the fit parameter are written in the plot. For an electricity demand of 5172 TWh/a, North America requires an energy storage capacity of 2.2 % (113.8 TWh) of the annual electricity demand (1 % is equivalent to 87.6 h of mean electricity demand) without excess power installed and with an exponential decline it ends at 0.15 % (7.8 TWh) of the annual electricity demand for 100 % excess capacity (a doubling of the power plant capacity).

The power plant mix for New Zealand is also at 10 % wind and 90 % PV power for the lowest energy storage requirements. Excess capacity leads in this case to a much slower decrease for the required energy storage and a reduction by a half only appears for an installed excess capacity between 10 % and 15 % of the minimum required power plant capacity (fig.: 5.13). The fit of the eq.: [5.3] with the parameters $a^* = 0.403$, $b^* = 4.954$ and $c^* = 0.07$ works quite well to describe this behaviour. So the lowest required energy storage capacity converges to 0.4 % (0.2 TWh) of the annual electricity demand of the region.

The model region of Asia comes with a 100 % PV power supply and the strongest reduction of energy storage for an increase of installed excess power. There the required energy storage is reduced by a half already at 4 % installed excess power (fig.: 5.14). Fiting eq.: [5.3] to this data workes well and leads to the parameters $a^* = 0.168$, $b^* = 1.687$ and $c^* = 0.181$. Therefore the lowest required energy storage converges to 0.17 % (15.4 TWh) of the annual electricity demand of Asia.

Africa has its lowest required energy storage capacity for an electricity supply as well with 100 % PV power, but a further reduction of the energy storage by installing excess power plant capacities is much slower than for Asia. A reduction of the required energy storage capacity appears at around 10 % excess power (fig.: 5.15). But in the case of Africa, the decrease of required energy storage goes further on and so it is the only case where the storage capacity for the 15 %, 20 % and 50 % excess power is overestimated by the fit of eq.: [5.3]. The parameters result with $a^* = 0.175$, $b^* = 5.44$ and $c^* = 0.088$.

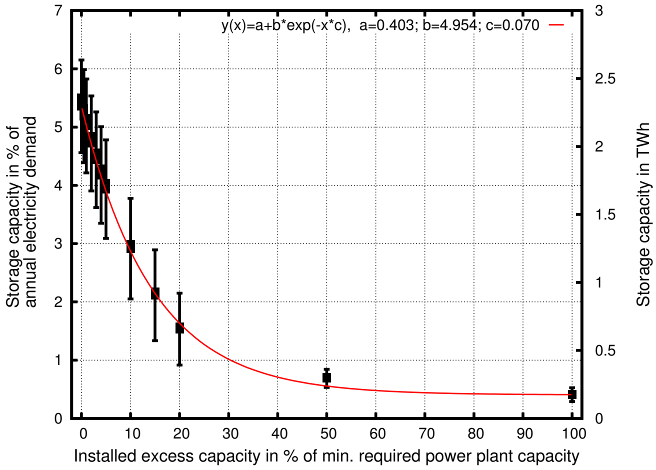


Figure 5.13.: Required energy storage capacity for installed excess power plant capacity from 0 % to 100 % of the minimum required power plant capacity in New Zealand for the 10 % wind and 90 % PV power scenario. Black dots for the mean required energy storage capacity calculated with the MEET model for the weather data from 2000 to 2010 and error bar for the one sigma standard deviation. The red line is the fit result of eq.: [5.3] and the fit parameter are written in the plot. For an electricity demand of 44 TWh/a, New Zealand requires an energy storage capacity of 5.4 % (2.4 TWh) of the annual electricity demand (1 % is equivalent to 87.6 h of mean electricity demand) without excess power installed and with an exponential decline it ends at 0.4 % (0.2 TWh) of the annual electricity demand for 100 % excess capacity (a doubling of the power plant capacity).

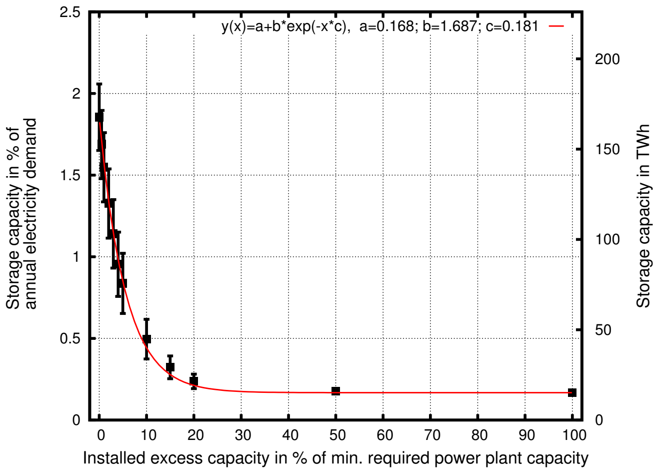


Figure 5.14.: Required energy storage capacity for installed excess power plant capacity from 0 % to 100 % of the minimum required power plant capacity in Asia for the 100 % PV power scenario. Black dots for the mean required energy storage capacity calculated with the MEET model for the weather data from 2000 to 2010 and error bar for the one sigma standard deviation. The red line is the fit result of eq.: [5.3] and the fit parameter are written in the plot. For an electricity demand of 9053 TWh/a, Asia requires an energy storage capacity of 1.9 % (172 TWh) of the annual electricity demand (1 % is equivalent to 87.6 h of mean electricity demand) without excess power installed and with an exponential decline it ends at 0.2 % (18.1 TWh) of the annual electricity demand for 100 % excess capacity (a doubling of the power plant capacity).

So the lowest required energy storage capacity converges to 0.18 % (1.9 TWh) of the annual electricity demand of the region.

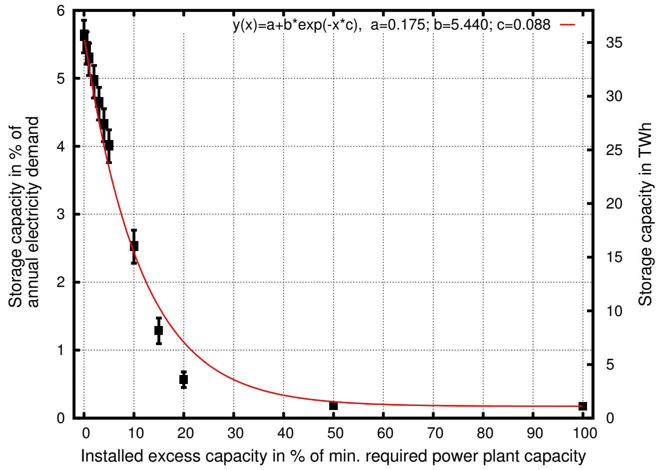


Figure 5.15.: Required energy storage capacity for installed excess power plant capacity from 0 % to 100 % of the minimum required power plant capacity in Africa for the 100 % PV power scenario. Black dots for the mean required energy storage capacity calculated with the MEET model for the weather data from 2000 to 2010 and error bar for the one sigma standard deviation. The red line is the fit result of eq.: [5.3] and the fit parameter are written in the plot. For an electricity demand of 638 TWh/a, Africa requires an energy storage capacity of 5.6 % (35.7 TWh) of the annual electricity demand (1 % is equivalent to 87.6 h of mean electricity demand) without excess power installed and with an exponential decline it ends at 0.2 % (1.3 TWh) of the annual electricity demand for 100 % excess capacity (a doubling of the power plant capacity).

So, for all model regions one can conclude that an increase of power plant capacity beyond the minimum required power, here called the excess power, leads to a strong reduction of the required energy storage capacity (for a summary of the simulation results see tab.: 5.1).

Table 5.1.: Summary of required energy storage capacity for varying excess capacity scenarios. Model regions with annual electricity demand, required power plant capacity to be installed as minimum, ratio of installed wind and PV power plant capacity and required energy storage capacity in % of the annual electricity demand as averaged value of the simulated years 2000 to 2010.

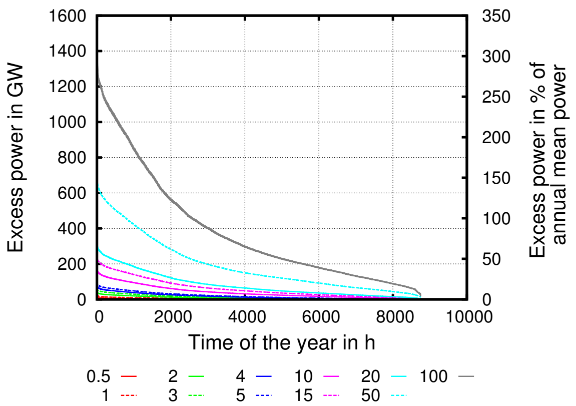
Model Region	El. demand [TWh/a]	Power plant capacity [GW]	Power ratio [%-wind / %-PV]	Installed excess power plant capacity in % of minimum required power plant capacity (in % of annual electricity demand) 0 %	0.5 %	1 %	2 %	3 %	4 %	5 %	10 %	15 %	20 %	50 %	100 %
Asia	9053	7751	0W / 100PV	1.85	1.69	1.55	1.33	1.14	0.95	0.84	0.5	0.32	0.24	0.18	0.17
North America	5172	3991	10W / 90PV	2.21	2.03	1.89	1.63	1.4	1.2	1.04	0.46	0.27	0.23	0.17	0.15
Europe	3956	2994	30W / 70PV	3.79	3.56	3.38	3.05	2.78	2.54	2.31	1.55	1.23	1.01	0.45	0.19
Africa	638	575	0W / 100PV	5.61	5.44	5.28	4.95	4.63	4.31	4	2.52	1.28	0.57	0.18	0.18
South America	1050	416	50W / 50PV	4.3	4.08	3.9	3.61	3.35	3.11	2.92	2.29	1.88	1.57	0.79	0.29
New Zealand	44	39	10W / 90PV	5.36	5.19	5.02	4.72	4.44	4.18	3.94	2.91	2.11	1.53	0.69	0.41
Australia	272	145	50W / 50PV	4.93	4.95	4.66	4.12	3.64	3.23	2.85	1.67	1.2	0.95	0.45	0.15

5.2.1. Additional electricity available by having excess power plant capacities installed

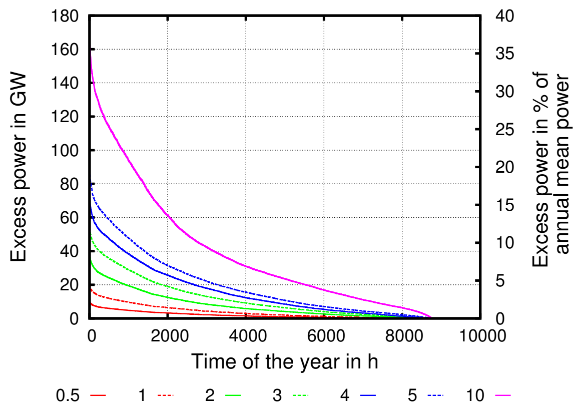
Of course, by having excess power capacities installed for an electricity supply scenario, additional electricity will be generated that is available for possible use. For the example of the model region of Europe the amount of electric energy that is available in addition to the scenarios of excess capacities is given in tab.: 5.2. The numbers have been calculated by using the weather data for 2009 and lead to an electricity excess from 0.4 % up to 83.8 % of the annual electricity demand for the different excess capacity scenarios. A reason why a 100 % excess capacity does not lead to a 100 % excess electricity is based on the limitation of high potential sites for wind and PV power plants (compare fig.: 3.9 and 3.8).

Table 5.2.: Excess electricity generated by the installed excess power plant capacity for Europe with a power plant ratio of 30 % wind and 70 % PV power capacity and the weather data of 2009 for the eleven excess capacity scenarios. The excess electricity beeing not required for the electricity supply of 3956 Twh/a is given in TWh and % of the annual electricity demand and could be used for any additional reason.

Scenario	0.5 %	1 %	2 %	3 %	4 %	5 %	10 %	15 %	20 %	50 %	100 %
[TWh]	17.2	34.3	69.4	104.9	140.4	175.8	353.6	532.0	707.7	1664.5	3313.5
[%]	0.4	0.9	1.8	2.7	3.6	4.4	8.9	13.5	17.9	42.1	83.8



(a)



(b)

Figure 5.16.: (a) Annual duration curves of additional and free available electric excess power for scenarios of 0.5 %, 1 %, 2 %, 3 %, 4 %, 5 %, 10 %, 15 %, 20 %, 50 %, and 100 % excess power plant capacity being installed to the Europe 30 % wind and 70 % PV power scenario for the weather data of 2009. Having excess power plant capacities installed, a small electric excess power will be available almost all over the year but for 2000 h or less, the excess electricity being available rises to respectable amounts. (b) Zoom for excess power plant capacities from 0.5 % to 10 %.

To get an idea on how the excess electricity could be used, it is important to know how long a certain amount of electric power would be available during a year. So the available excess electric power has been plotted as an annual duration curve for Europe while sorting the hourly electric excess power by their size (fig.: 5.16 (a) and (b)). The most power would be only available for a few hours and the minimum guarantied power declines fast during a rising availability time. Even for an availability time of 2000 hours per year, the available excess power is less than a half of its annual maximum. The concrete values of excess power that could be used for 25 %, 50 %, 75 % and 100 % of a year for the model region of Europe are given by tab.: 5.3.

Table 5.3.: Guaranteed availability of excess power in GW and in % of annual mean power during the year for Europe with 30 % wind and 70 % PV power and the weather data of 2009 for the eleven excess capacity scenarios from 0.5 % to 100 %. A guaranteed availability of for example 50 % in the case of having 4 % excess power plant capacity installed lead to the fact that about 11 % of the required annual mean power would be available for the time of half a year.

	Minimum available excess power										
Availability [%]	0.5 % [GW]	1 % [GW]	2 % [GW]	3 % [GW]	4 % [GW]	5 % [GW]	10 % [GW]	15 % [GW]	20 % [GW]	50 % [GW]	100 % [GW]
25	3.0	6.1	11.5	17.7	23.9	29.6	56.4	847	111.8	260.9	527.3
50	1.3	2.6	5.2	8.0	10.9	13.6	28.1	43.1	57.1	137.6	268.0
75	0.4	0.8	1.9	3.1	4.1	5.5	13.6	21.5	30.0	76.6	151.9
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	11.1	19.1

	Minimum available excess power										
Availability [%]	0.5 % [%]	1 % [%]	2 % [%]	3 % [%]	4 % [%]	5 % [%]	10 % [%]	15 % [%]	20 % [%]	50 % [%]	100 % [%]
25	0.7	1.3	2.6	3.9	5.3	6.5	12.5	18.7	24.7	57.7	116.7
50	0.3	0.6	1.1	1.8	2.4	3.0	6.2	9.5	12.6	30.4	59.3
75	0.1	0.2	0.4	0.7	0.9	1.2	3.0	4.8	6.6	16.9	33.6
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	2.5	4.2

5.3. Comparison of required energy storage capacity for Europe and Germany

An electricity supply based on wind and PV power plants is highly dependant on the weather. So as cyclones typically have a diameter of roughly 1000 km (Kraus, 2004) and clearly determine the weather in the west wind zone, the size of an area for electricity supply should have an influence on the opportunity to balance wind and solar power. To investigate this point, again the model region of Europe as part of the west wind zone was used for this section. For the simulation of a region smaller than Europe and in the order of a cyclone, Germany was chosen. To do so, the option of the MEET model to define an individual region was used. So a rectangle, overlying the region of Germany, with the coordinates for the south-west corner at 47.5 N and 7.5 E and the north-east corner at 52.5 N and 12.5 E was given to the MEET model.

To obtain more comparable results, the annual electricity demand for the model region of Germany was set to 168.3 TWh to get the same electricity demand per km^2 as the model region of Europe. The Results based on this setup are marked in the following as Germany*. But also simulations for Germany with its original electricity demand of 639.1 TWh from the year 2008 BP (2009) have been made. To allow all electricity supply scenarios for Germany from an use of 100 % wind power to 100 % PV power plants, the maximum allowed area share for wind power plants needed to be extended from 5 % to 10 % to place the required capacities, which is still feasable (Bofinger et al., 2011). The allowed area share for PV power plants needed to be extended aswell from 0.6 % to 1.4 %, which exceeded the at Braun and Oehsen (2012) assumed 0.8 %, but it is not totally out of range and is only needed for the very high PV scenarios.

5.3.1. The influence of wind and PV power ratio on the required energy storage for Germany

With regard to the required energy storage capacities, the used weather data of 2009 was closest to the mean required energy storage capacity for the 30 % wind and 70 % PV power scenario of Europe (section 5.1). Nevertheless, the minimum required energy storage capacity comes out in this case for a 40 % wind and 60 % PV power mix, with 2 % (79.1 TWh) of the annual electricity demand of Europe (fig.: 5.17(a)). For the much smaller region of Germany, the power plant mix requiring the smallest energy capacity is also at 40 % wind and 60 % PV. Regarding the relative amount of the energy storage capacities, the Germany* scenario requires about double capacity with 4.1 % (6.9 TWh) of the adjusted electricity demand and using the real electricity demand of Germany, the required capacity reaches actually 4.5 % (28.8 TWh) of the annual electricity demand (fig.: 5.17(a)).

The required energy storage capacity for wind and PV power can be described in analogy to section 5.1 by a polynomial fit of eq.: [5.1]. For Germany a polynomial of the order of four leads to the parameters $a = 16.597$, $b = -3.191$, $c = 0.151$, $d = -0.005$ and $e = 0.002$.

For most other power plant installations as well, the required energy storage capacity in percentage of the annual electricity demand is lower for the Europe scenario than for the Germany and the Germany* scenarios too. Only for the range from 80 % to 60 % of wind power ratio, the Germany* scenario comes out with a relative storage capacity lower than Europe. Comparing the Germany and Germany* scenarios, the Germany scenario requires about 10 % to 20 % more relative energy storage capacities than the Germany* scenario except for the 60 % wind power ratio.

Regarding the generated electricity, at the 40 % wind and 60 % PV power scenario for Germany, 55 % of the electricity has been generated by wind power plants (fig.: 5.17(b)). So it is again similar to the Europe scenario of section 5.1, where the lowest required energy storage capacity occured as well for

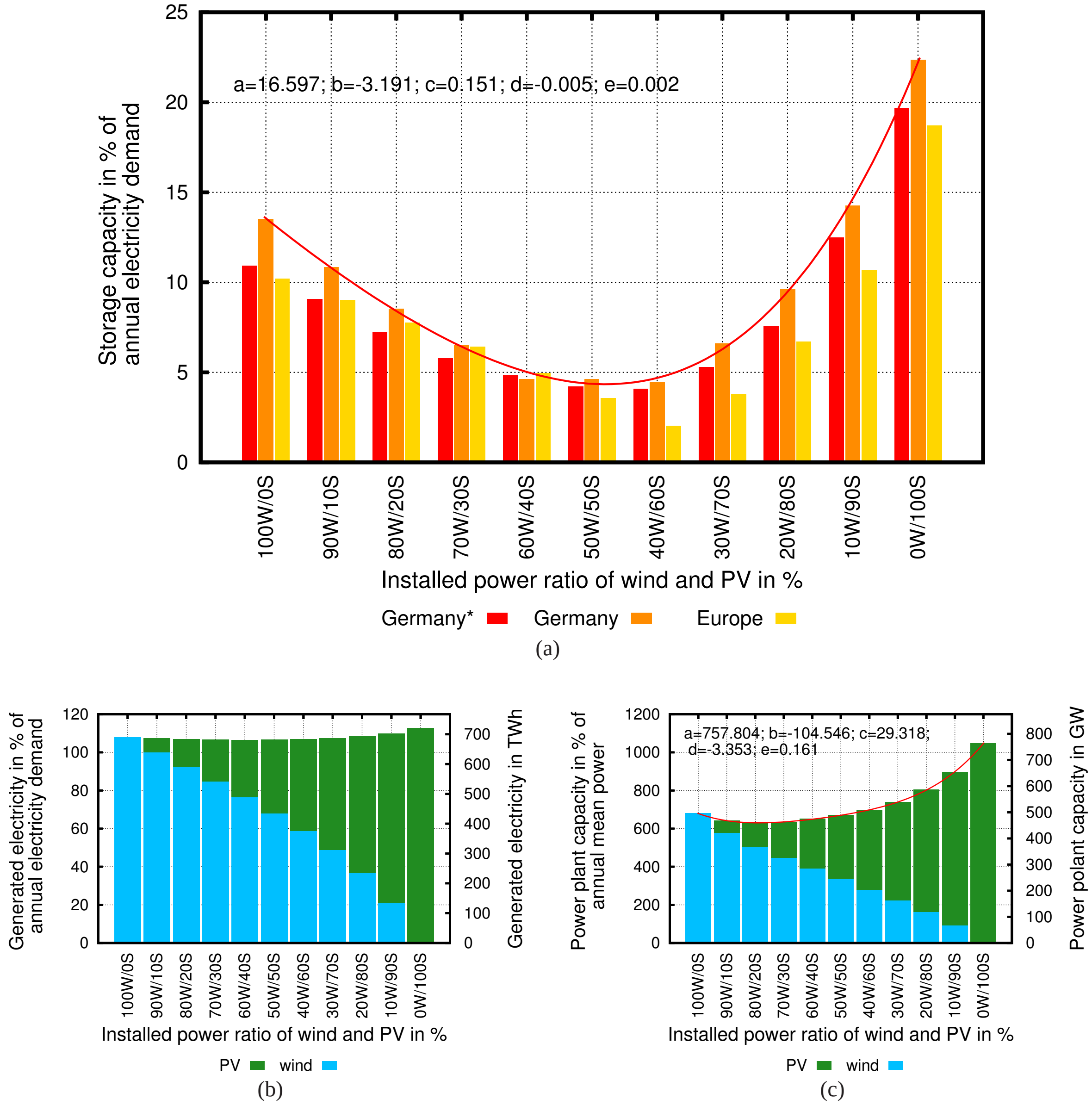


Figure 5.17.: Electricity supply of Europe (3956 TWh/a), Germany (639 Twh/a), and Germany* (168 TWh/a) for varying ratios of installed wind and PV power plant capacities starting at the left with 100 % wind and 0 % PV power and going by 10 % steps to a 0 % wind and 100 % PV power scenario calculated by using weather data of 2009. (a) Required energy storage capacity of Europe, Germany and Germany*. Compared to fig. 5.2, where the mean required energy storage capacity of the years 2000 to 2010 has its minimum at a ratio of 30 % wind and 70 % PV power, the minimum is located at 40 % wind and 60 % PV power. Due to its larger area, Europe requires less energy storage capacity as the variation of weather is increased compared to the small area of Germany. The red line is the fit of eq.: [5.1] to describe the required energy storage capacity for the Germany scenario. (b) Generated electricity by wind and PV power for the Germany scenario. (c) Required power to be installed for the electricity supply of Germany, rising for increased PV power but the minimum is not at the 100 % wind power scenario as the limited area of Germany forces to use wind power sites being worth than the best PV sites. The red line is the polynomial fit to describe the required power plant capacity for the Germany scenario.

a balanced electricity generation. In total, the generated electricity has a very slight reduction with the minimum at 40 % ratio of PV power and rises to its maximum for a 100 % ratio ov PV power.

In contrast to Europe (fig.: 5.2(c)), the Germany scenario shows a slight reduction even for the needed power plant capacity down to 630 % of the on-average required power going to the 80 % wind power ratio (fig.: 5.17(c)). From there the power rises as usual in an exponential way for a rising ratio of PV power plants up to 1046 % of the annual mean power for the 100 % PV power supply. Due to this behaviour a exponential fit as done in section 5.1 does not work to describe the behavior of required power plant capacity on the power plant mix. Therefore again a polynomial of the order of four with the parameters $a = 757.804$, $b = -104.546$, $c = 29.318$, $d = -3.353$ and $e = 0.161$ works well.

5.3.2. The effect of excess power plant capacity for Germany's energy storage capacity

To understand how the required energy storage capacity of Germany could be reduced by installing excess capacities of wind and PV power plants, the mix of 40 % wind and 60 % PV power has been choosen as it already requires the lowest storage capacity. Even if the effect is not as strong as for the region of Europe, the required energy storage capacity could be reduced by a half for 15 % of installed excess power (fig.: 5.18). An exponential function as eq.: [5.3] fits as well to the general behaviour and converges to 0.74 % of the annual electricity demand. But in fact, the fit overestimates the required energy storage capacity for the 100 % excess power scenario and underestimates the 50 % value.

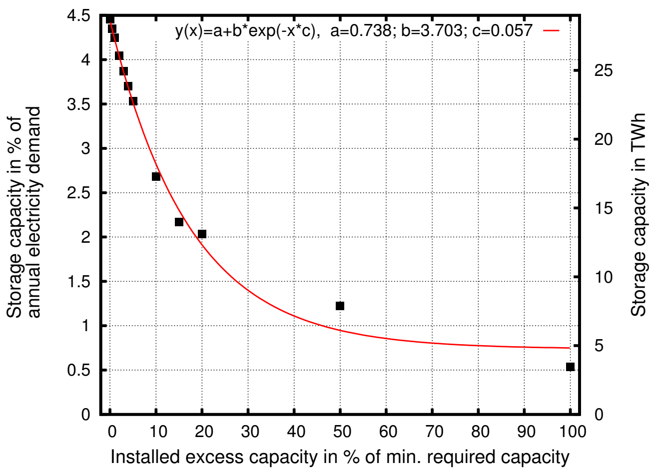


Figure 5.18.: Required energy storage capacity for installed excess power plant capacity from 0 % to 100 % of the minimum required power plant capacity for electricity supply in Germany for the 40 % wind and 60 % PV power scenario. Black dots for the required energy storage capacity calculated with the MEET model for the weather data of 2009. The red line is the fit result of eq.: [5.3] and the fit parameter are written in the plot. For an electricity demand of 639 TWh/a, Germany requires an energy storage capacity of 4.5 % (28.8 TWh) of the annual electricity demand (1 % is equivalent to 87.6 h of mean electricity demand) without excess power installed and with an exponential decline it ends at 0.5 % (3.4 TWh) of the annual electricity demand for 100 % excess capacity (a doubling of the power plant capacity).

So the principal behaviour for the model region of Germany and Europe comes out as quite similar, but the requirements related to the area or the annual demand are higher for Germany than for Europe.

5.4. The transition of Europe's electricity supply to wind and PV power

In this section, only the model region of Europe will be observed. Due to the fact that planning and installation of new energy storage capacities requires perhaps years, it is important to know in advance the dependency of required energy storage capacities on power plants using uncontrollable renewable energies, such as wind and solar power. Therefore, the focus is on the requirements of energy storage plants for an increasing share of wind and PV power plants.

Starting from the power plant setup of Europe for the year 2007 given in the energy [r]evolution study (Teske et al., 2010), the installed power plant capacities have been changed for the simulations in the way that the sum of PV and wind power rise in steps of ten percent of the total power plant share. As a final scenario, an electricity supply of 30 % wind and 70 % PV power plants has been choosen as it requires the lowest storage capacities for a 100 % wind and PV power based scenario (fig.: 5.2 (a)). To ensure that a changing ratio of wind and PV power will not influence the results of the different scenarios, the installed capacities of these two power plant types have been adjusted already for the setup of 2007 to the 30 % to 70 % ration of the goal scenario and remain constant at this ratio for all steps.

5.4.1. Energy storage requirements for a rising share of renewable energies

At the beginning of the transition, the volatile electricity generation of wind and PV power can be easily compensated without an energy storage. For a 30 % share of wind and PV capacities on the total installed power plants, the MEET model makes use of the energy storage for the first time (fig.: 5.19). Starting with an energy storage capacity of of 0.013 % (0.5 TWh) for Europes annual electricity demand, the required storage capacity rises exponentially with an increasing share of the installed wind and PV power. The growth rate of the needed storage gets reduced only between the 40 % and 50 % fraction of the power plant share and coming closer to the 100 % wind and PV scenario, which ends at 3.8 % (148.8 TWh) storage capacity of the annual electricity demand.

When additional wind and PV power plants is installed to the 100 % scenario, this excess capacity leads to a reduction of the required energy storage capacity (compare section 5.2). For a 100 % excess capacity, which means 200 % of required power plant capacity, the energy storage will be reduced to 0.2 % (9.5 TWh) of the annual electricity demand (fig.: 5.19). The reduction goes in two major steps. A strong reduction for the first 20 % of excess capacity followed by a slower reducing effect. This could be explained by two effects: 1) when adding further power plant capacities in the MEET model, the efficiency of this power plants goes down as the best sites for renewable energies were used first. 2) the reduced energy storage capacity is for compensating smaller periods of deficits and thereby the installed excess capacity is less efficient in reducing the required energy storage (see section 5.5 and fig.: 5.24 as well).

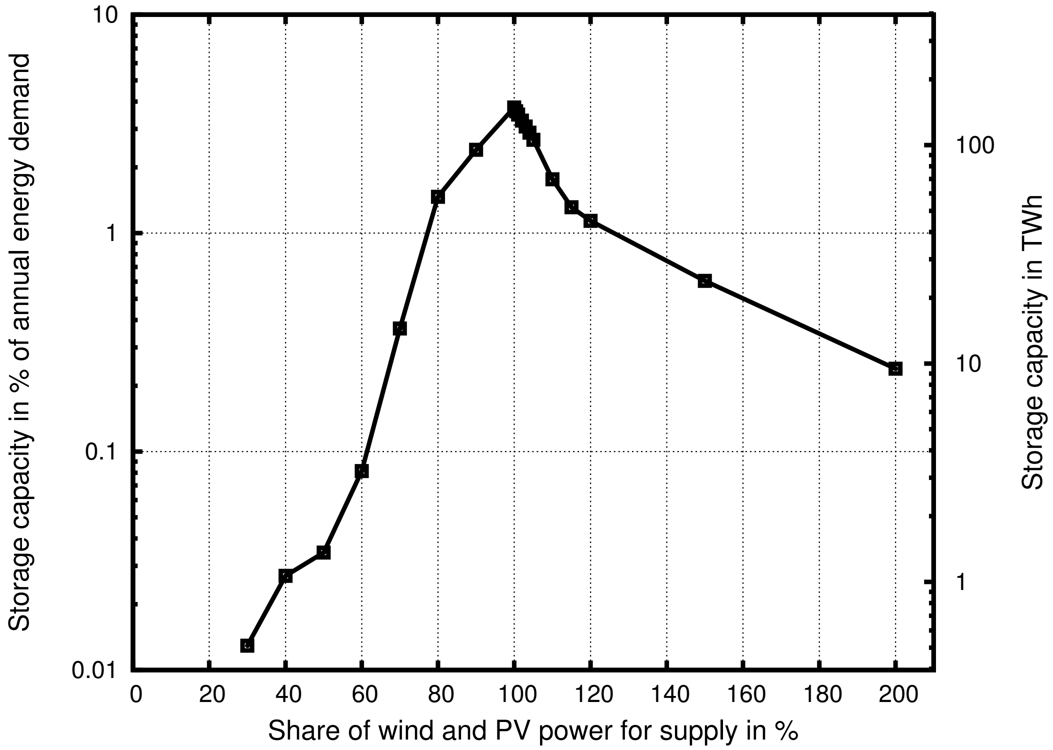


Figure 5.19.: Required energy storage capacity in Europe for the transition from the power plant mix of 2007* (Teske et al., 2010) to the 30 % wind and 70 % PV power scenario with weather data of 2009. The share of wind and PV power on the total power plant capacity is increased in 10 %-point steps. Once the 100 % renewable scenario is reached, up to 100 % excess wind and PV power plant capacity is installed, leading to ’200 % share’ of required wind and PV power plant capacity. The required energy storage capacity increases fast once the share of weather dependent renewable power plant capacities exceeds 50 % and reaches its maximum at 100 % renewable power with a storage capacity of up to 3.8 % of the annual electricity demand. The installation of excess capacity as described in section 5.2 lead to a fast reduction, but at 20 % excess capacity the effect is reduced. (* The wind and PV power capacity have been changed into a 3 to 7 ratio.)

5.4.2. Use of power plants during the electricity supply transition

During the transition to the renewable energies based electricity supply system, the different power plant types need to change the degree of capacity utilisation to fit the new requirements. The full load hours of the site dependent wind and PV power plants get reduced with increasing capacity share (fig.: 5.20) as the prime sites have been used by the MEET model at first and additional capacities need to be placed at regions with reduced potentials. The runoff river hydro power remains at 2628 full load hours as it is given to the MEET model (section 3.9). The utilized capacity of bio power plants should not be considered, as the full load hours are hardly dependent on the installed power and the constraint of 137 TWh/a (tab.: 3.5) as maximum electricity generation by bio power plants for Europe. The nuclear and coal power plants start at too high a level of full load hours, as discussed in section 4.3. But their behaviour of utilization reduction due to the rising share of wind and PV power, with priority on the electricity feed-in, is well represented (fig.: 5.20). So the nuclear power plants which have the longest cool down time (tab.: 3.6) are only able to keep the full load hours up to a wind and PV power share of 40 % on the high level. Already after the 50 % share, the utilised power of nuclear power plants becomes lower than the coal power plants and hardly declines. The coal power plants need to follow the fast declining trend after a share of 60 % of power capacity is given by wind and PV power. Only the flexible gas power plants start to increase their full load hours after wind and PV power plants reach a share of 30 % on the total power capacity. After a share of 50 % gas power plants are even more often needed to compensate the volatile electricity generation of the wind and PV power plants.

The total power plant capacity needed to be installed rises faster with an increased share of wind and PV power (fig.: 5.21 (a)). So the installed power plant capacity starts at 173 % (780 GW) of the annual mean power required to meet the demand of Europe and rises up to 670 % (3028 GW) for the power supply by 100 % wind and PV power. The share of generated electricity starts clearly dominated by the gas, coal and nuclear power plants (fig.: 5.21 (b)). After 50 % of installed power is given by wind and PV power plants, the share of electricity generated by nuclear and coal power plants declines quickly, while gas power plants mainly stay on their share of electricity generation. Having 80 % or more of power plant capacity given by wind and PV power, the electricity generation needs to exceed the annual electricity demand, which is based on the losses for the energy storage activities.

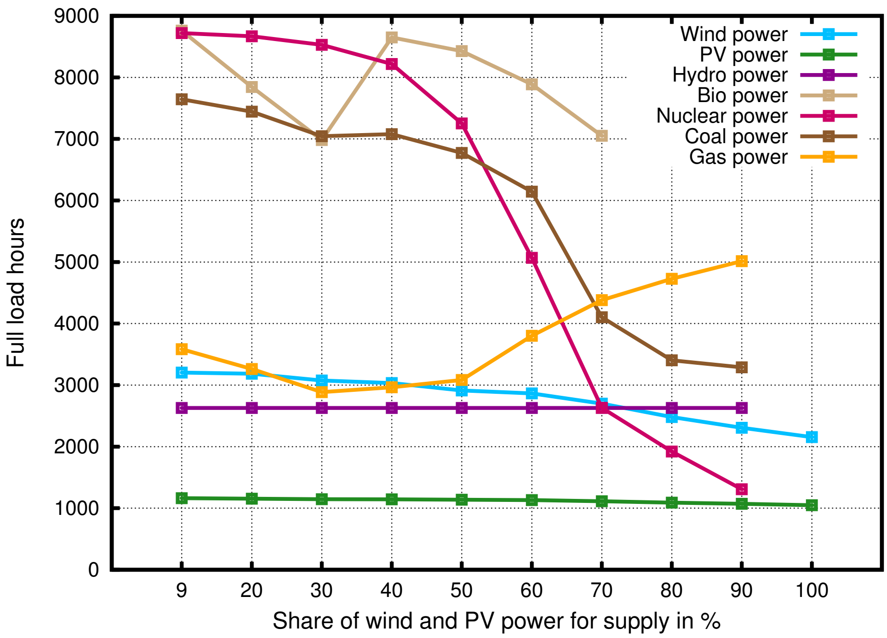


Figure 5.20.: Full load hours of power plants for the transition from the power plant mix of 2007* (Teske et al., 2010) to the 30 % wind and 70 % PV power scenario with weather data of 2009. The share of wind and PV power on the total power plant capacity is increased in 10 %-point steps. While the full load hours of nuclear and coal power plants decrease for a rising share of weather dependent wind and PV power plants, the gas power plants have to be used more often to compensate fluctuations in electricity supply. (* The wind and PV power capacity have been changed into a 3 to 7 ratio.)

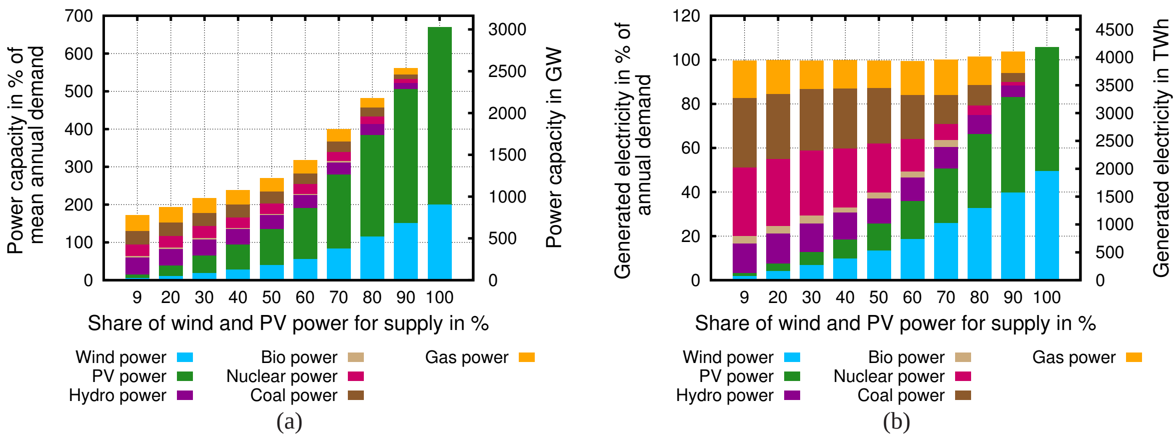


Figure 5.21.: (a) Installed power plant capacities for the transition scenario in Europe as in fig.: 5.20. Because the utilised capacity of wind and PV power plants is much lower than for the other power plants (fig.: 5.20), the total power plant capacity required for the supply increases fast with the share of wind and PV power from 173 % to 670 % of the power being required in the annual mean. (b) By power plant type generated electricity for the transition scenario in Europe. The slight variation of the total electric energy being generated during the year is based on the losses when using the energy storage.

5.5. The requirements on energy storage facilities during a year

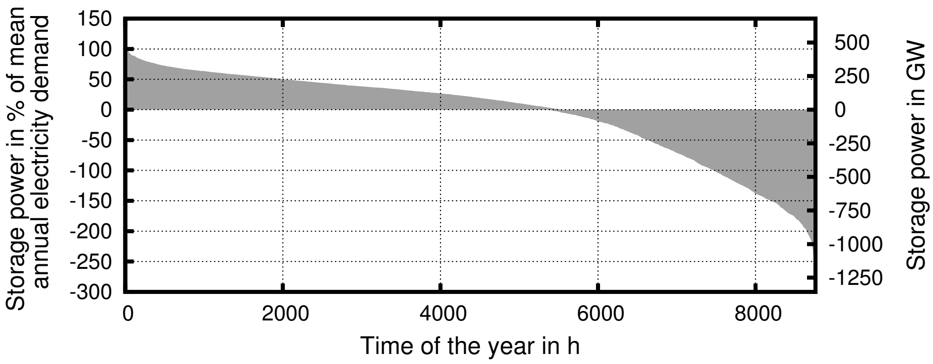
To show the way the required energy storage capacity is used and what the requirements on energy storage facilities are over the course of a year, the hourly charging and discharging rates have been investigated. This is important to decide for the best technology to use to balance the electricity supply since the energy density and the efficiency of energy conversion vary quite strongly among energy storage types such as pumped hydro power, compressed air energy storage or hydrogen and methane storage (Bünger et al., 2009). So not only the total storage capacity, but also the required power and the frequency of use has to be considered for organizing an energy storage infrastructure.

Looking on the example of the 30 % wind and 70 % PV power scenario of Europe without excess capacity and for the weather data of 2009, the time where the energy storage is needed to compensate a deficit in electricity supply is clearly longer with 5444 h than the periods where excess energy can be stored with 3316 h (fig.: 5.22 (a)). Further the annual load duration curve of the power of the energy storage for the mentioned scenario shows that the rated power of the energy storage needs to be more than two times higher for storing (charge) than for generating electric power (discharge). The maximum power capacities for carging and discharging the storage are rarely used during the year which can be seen at the high peaks at the left and right border of fig.: 5.22 (a), but then the slope of the load duration curve stays relativly constant during the main time.

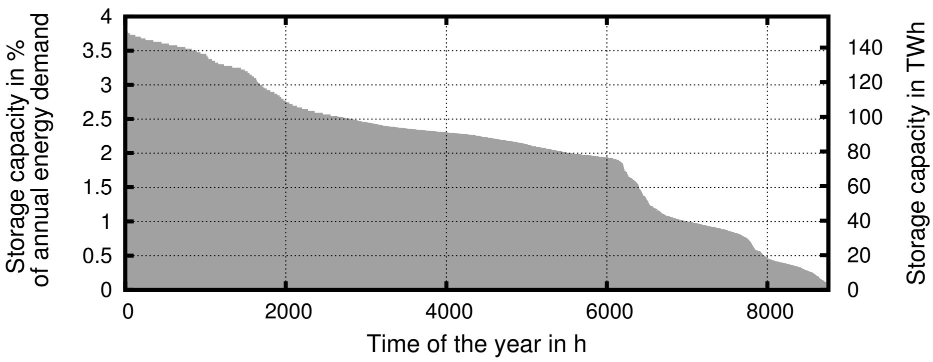
Of course the required charging power of the energy storage seems to be quite high as it is 1190 GW (264 % of the on-average required electric power of the supply region). Obtaining this power in relation to the total energy storage capacity of 148.8 TWh, the scenario for the MEET model comes out with

1 kW power per 125 kWh storage capacity. This ratio is totally in range or even up to a factor of ten less power per storage capacity compared to existing pumped hydro power energy storages presented in Bünger et al. (2009) and therby feasable.

The filling level of the energy storage reaches its maximum for the 30 % wind and 70 % PV power scenario without excess capacity at 3.8 % (148.8 TWh) of the annual electricity demand. From there, the annual duration curve of the stored energy (fig.: 5.22 (b)) starts with a fast reduction of the used storage capacity, followed by a filling level between approximately 2.5 % and 2 % of the annual electricity demand that covers round about half of the time during the year. Finally, the lower storage filling levels again vary much faster.



(a)



(b)

Figure 5.22.: (a) Annual load duration curve of energy storage power with negative values for charge and positive values for discharge the storage for the 30 % wind and 70 % PV power scenario of Europe without excess capacity and for the weather data of 2009. Discharge takes place for about 5444 h a year and charge for 3316 h. The required charge power is about two times larger than the discharge power. (b) The annual duration curve of stored energy, having a flat region in the middle foe about half a year time.

5.5.1. Separation into long and short time storage

Looking on the stored energy over the course of a year for the example of the 30 % wind and 70 % PV power scenario without excess capacity and the weather of 2009, the maximum stored energy occures in October (fig.: 5.23 (a)). So in this PV power dominated case, the storage mainly get charged during the summer season and needs to be used during winter time. But the seasonal storage trend is overlayed by a dayly variation mainly based on the PV power that can be seen by zooming into the timeline; for example, to the week of the 19th to 25th January 2009 (fig.: 5.23 (b)).

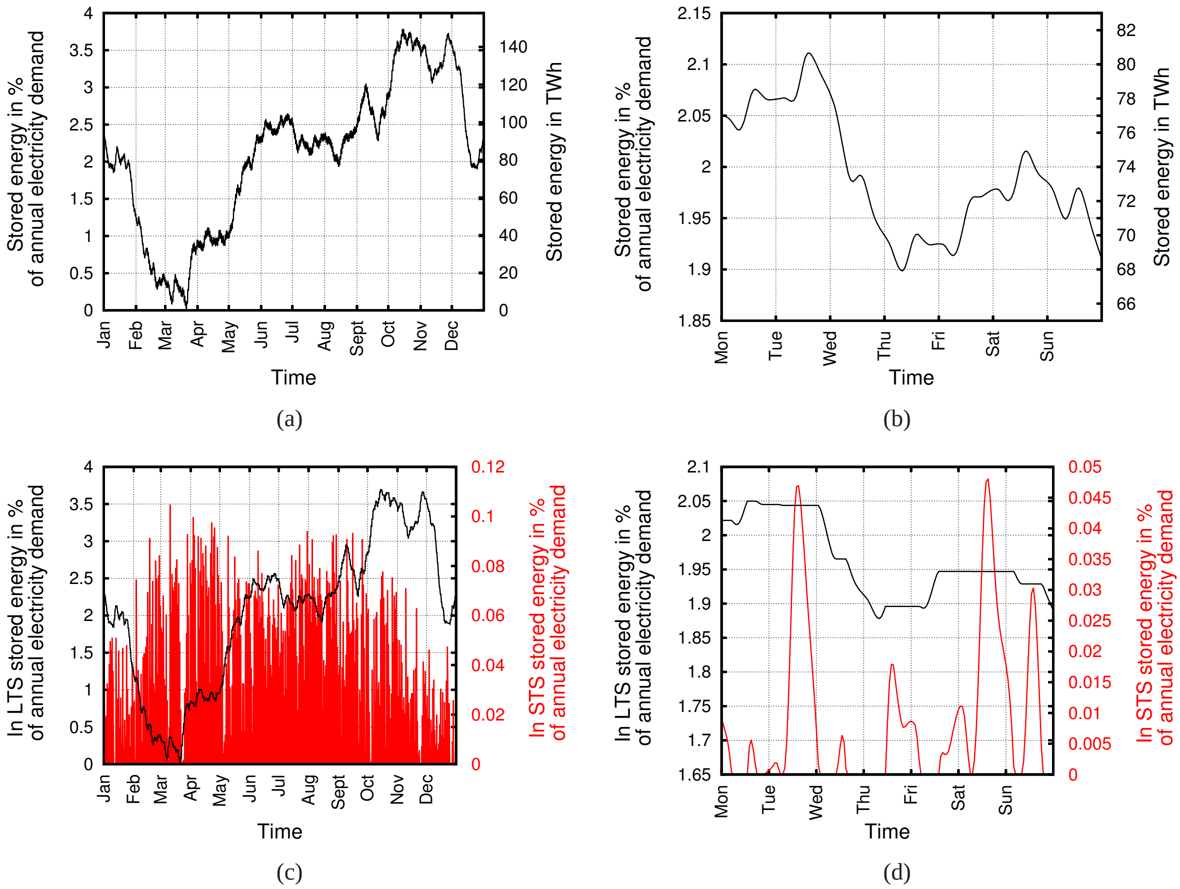


Figure 5.23.: (a) Stored energy during the year for the 30 % wind and 70 % PV power capacitc scenario of Europe wihout excess power for the weather data of 2009. (b) Zoom into the week from 19th to 25th January. (c) Stored energy of long time storage (LTS) (black line) and short time storage (STS) (red line) during the year. The maximum storred energy of lts and sts occure not at the same time, so the total storage capacity is slightly larger in this case than for one single storage type. (d) Zoom into the week from 19th to 25th January.

Regarding the different overlying frequencies of storing energy and the different requirements of the energy storage, it makes sense to separate the storage tasks to an long time storage (LTS) and short time storage (STS). A frequency analysis of time series calculated by the MEET model showed a 24 h time range as a good criteria for separation of a long and short time storage (Götz, 2013). Therefore, a tool developed by Götz (2013) was used to split the energy storage time line of the MEET model into the

STS part with storage cycles equal or shorter than 24 h and LTS part (fig.: 5.23 (c)). As the PV power specially needs to be compensated by the STS, its use is increased during the summer period. The STS now levels out the daily fluctuations given in fig.: 5.23 (b) and reduces the use of the LTS (fig.: 5.23 (d)).

To investigate on the behaviour of long and short time storage, the separation of the MEET model energy storage time line has been done for all transition scenarios from a conventional to an 100 % renewable electricity supply (section 5.4) and the excess power scenarios (section 5.2) for the model region of Europe and the weather data of 2009. The LTS and the STS tend to rise exponentially with an rising share of wind and PV power (fig.: 5.24 (a)). But the adding of excess power only reduces the demand of LTS while the required STS capacity remains almost constant.

While the maximum capacity of the LTS is about 30 times larger than the STS capacity (fig.: 5.24 (a)), the annual volume that goes through these two storage types is about the same or even higher for a high share of renewable power (fig.: 5.24 (b)). So for the 100 % scenario, more than 10 % of the annual required electric energy passes eiter the LTS or the STS. For both storage systems, the annual volume rises as well exponentially with the share of renewable power and is reduced by adding excess power plant capacities.

The number of total cycles the storage systems complete per year is anti-correlated once the share of installed renewable power exceeds 60 % (fig.: 5.24 (c)). For the 100 % scenario, the LTS only gets 2.9 full cycles per year of its energy storage capacity. The STS reaches 165.6 cycles per year, which means approximatly one full cycle all 53 h.

Knowing that different energy storage systems typically have either a high efficiency or a high energy density, the separation into long and sort time storage might be useful, but it leads in total to a slightly increase of the total storage capacity. So while the 30 % wind and 70 % PV power scenario comes with an required energy storage capacity of 148.8 TWh for Europe, a spliting leads to 146.2 TWh for the LTS and 4.1 TWh for the STS. This is in total an increase by 1 % of the in-total required energy storage capacity.

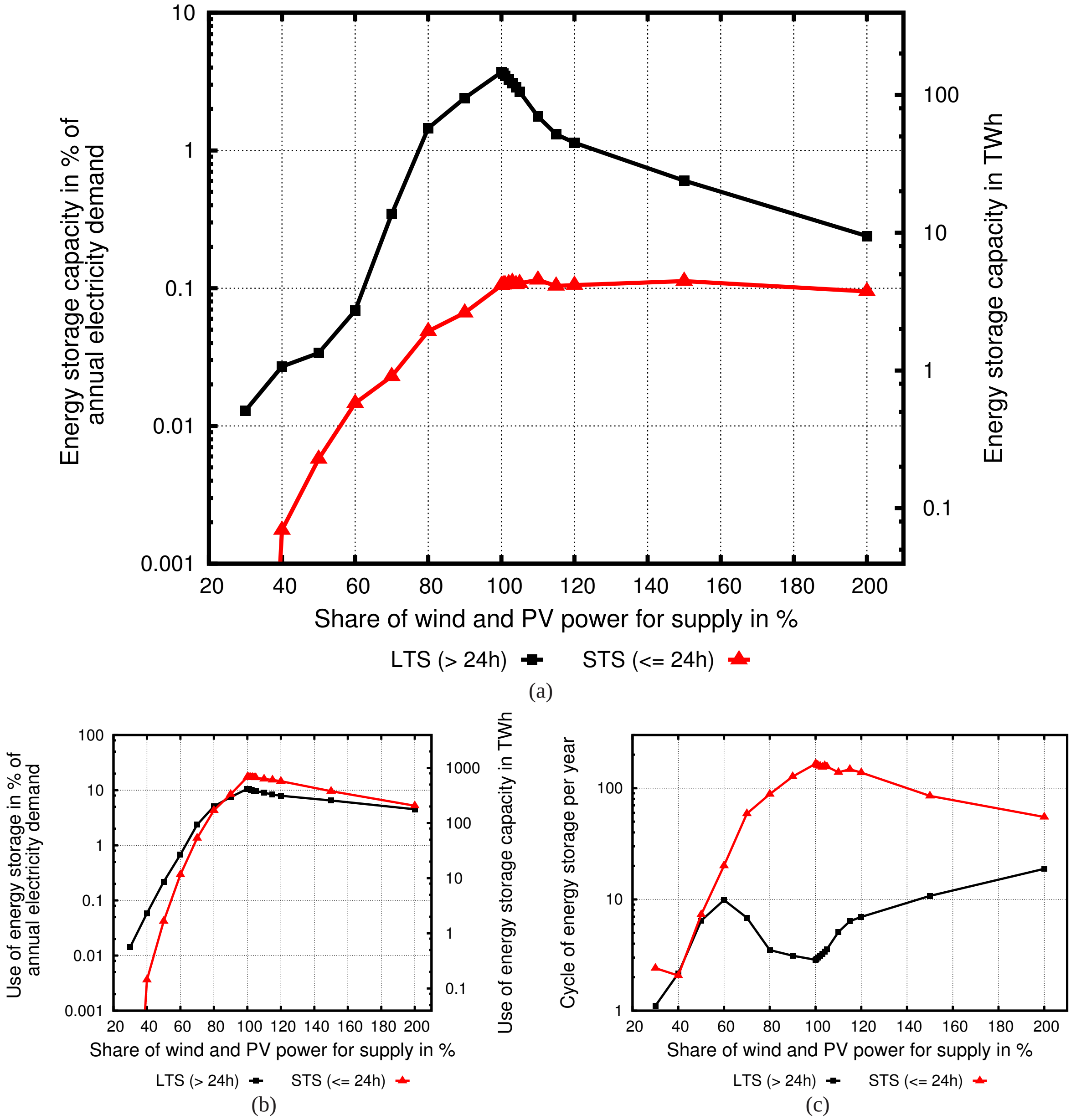


Figure 5.24.: Transition from the power plant mix of 2007* (Teske et al., 2010) to the 30 % wind and 70 % PV power capacity scenario with weather data of 2009. The share of wind and PV power on the total power plant capacity is increased in 10 %-point steps. Once the 100 % renewable scenario is reached, up to 100 % excess wind and PV power plant capacity is installed, leading to '200 % share' of required wind and PV power plant capacity. (a) Required long time storage (LTS) and short time storage (STS) capacity. Both storage capacities rise up to the 100 % renewable scenario, but the LTS requires about 30 times more capacity than the STS. The installation of excess power plant capacity almost effects the LTS. (b) Annual volume of stored energy at the LTS and STS. For the high share of wind and PV power scenarios, the STS stores about the same amount of energy as the LTS. (c) Amount of annual total cycles of LTS and STS. For the 100 % scenario the STS does about 165 cycles of its energy storage capacity while the LTS only does about 3. Therefore a high efficiency is required for the STS to minimise losses. For increased excess power, the number of annual cycles rise for the LTS as its capacity declines. (* The wind and PV power capacity have been changed into a 3 to 7 ratio.)

5.6. Influence of increased full load hours for wind power plants on electricity supply

In this section, the effects on the electricity supply of a possible increase of full load hours of onshore wind power plants will be investigated for the model region of Europe. As this would mean that a volatile electricity source could increase its annual availability, the focus is set to the required energy storage capacities and the power plant capacities itself.

In the last 30 years, new wind power plants tend to rise in their hub hight, rotor diameter and rated generator power as well quite fast to get the maximum electric energy at the sites and to reduce the levelized electricity costs (Wiser et al., 2011). For the relatively expensive placement of offshore wind power plants and the good wind conditions at their sites, this concept still makes sense, but for the onshore wind power plants things seem to change a bit. Modern onshore wind power plants tend to have a reduced generator capacity in relation to the hub hight and the rotor diameter (van der Hoeven, 2013). This leads to the fact, that such a wind power plant reaches its rated power at even lower wind speeds (fig.: 5.25) and thereby the availability and the annual utilised capacity in terms of full load hours rises.

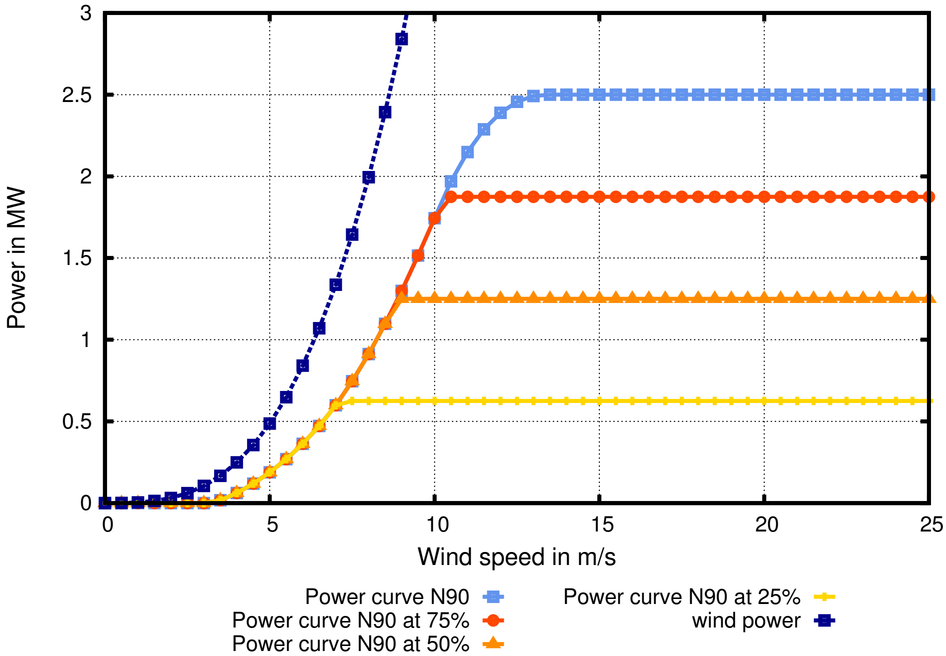
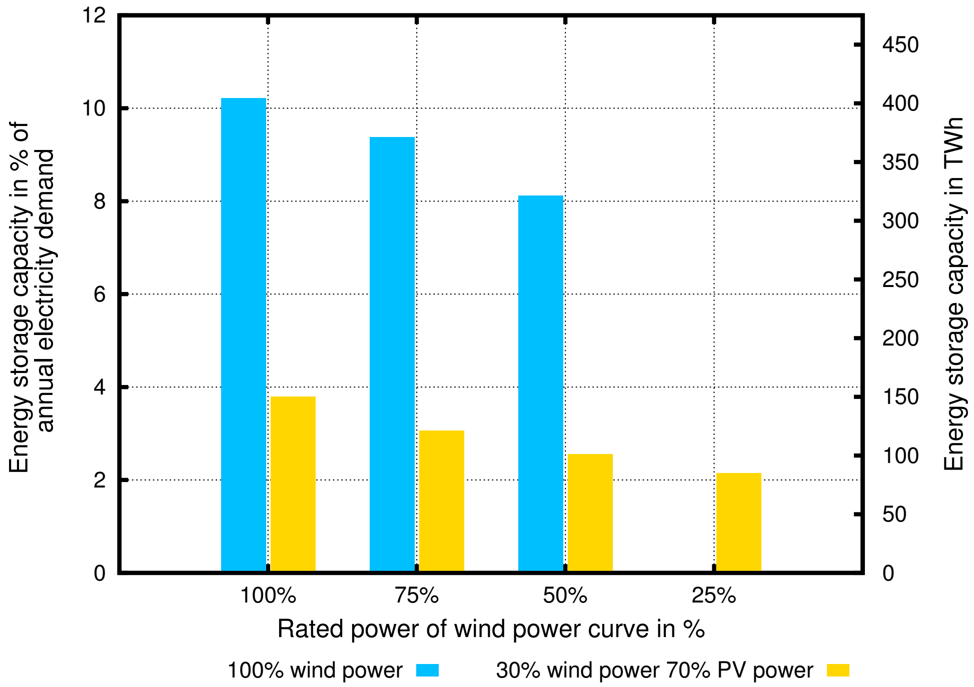


Figure 5.25.: Fictive reduction of the rated generator power of the Nordex N90 power curve to 75 %, 50 % and 25 % of the original power.

An increased availability of the wind power plants could be interesting for future electricity markets like direct selling of electricity generated by wind power, but the more continuous feed in effects the required energy storage capacities as well. In the case of the MEET model region of Europe the required energy storage capacity could be reduced by 20 % for the 100 % wind power scenario using windpower plants at 50 % reduced generator power. For the 30 % windpower and 70 % PV power scenario, even using wind power plants at 25 % of the original generator power reduced the required energy storage only by 12 % (fig.: 5.26(a)).

Because only the generator power, but not the wind power plant size was reduced, there is a higher demand for land in which to place the required wind power. So for the at 25 % rated wind power plants, the required area even exceeds the allouwed land share of 5 % of the MEET model for the 100 % wind power scenario.

Indeed the required area per installed kW peak power rises while reducing the rated generator power, but because the full load hours of these wind power plants rise as well (fig.: 5.26(c)), there is less power capacity to be installed (fig.: 5.26(c)). This counters the increased area demand at least for a while. So for the 100 % wind power scenario, the required power capacity is reduced by 35 % for wind power plants ratet at 50 % power and their full load hours increases from 1776 h by 52 % to 2707 h. For the 30 % wind and 70 % PV power scenario, the full load hours reach even 3048 h for the 50 % rated plants, as in this scenario fewer wind power plants need to be installed at sites having poor wind conditions.



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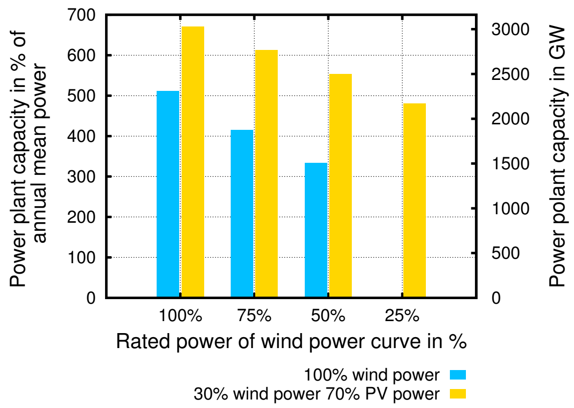

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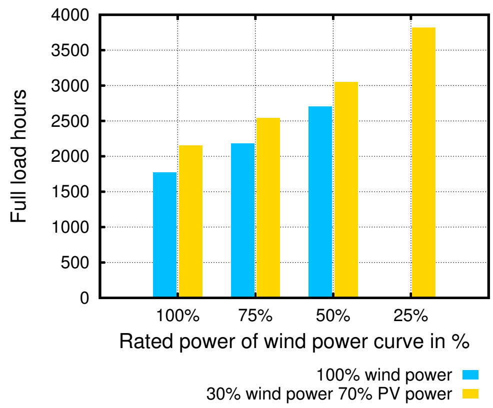


(c)

Figure 5.26.: Europe scenario with an electricity demand of 3956 TWh/a for 100 % wind power installed (blue) and 30 % wind and 70 % PV power installed (yellow) with the weather data of 2009. The used power curve for wind power simulation was set to 100 %, 75 %, 50 % and 25 % of the original power curve (fig.: 5.25) by keeping the rotor diameter constant to increase the full load hours. (a) Required energy storage capacity going down with rated power of the wind power curve due to a higher availability of the installed power capacity. (b) Required power to be installed for the electricity supply decreasing with the rated power as the full load hours increase. (c) Full load hours of wind power plants increase with a reduced generator power of the wind turbines. The 100 % wind power scenario is missing for the wind power plant at 25 % of the rated power as the required number of wind power plants exceed the allowed area to be installed.

5.7. Substituting PV power by CSP plants

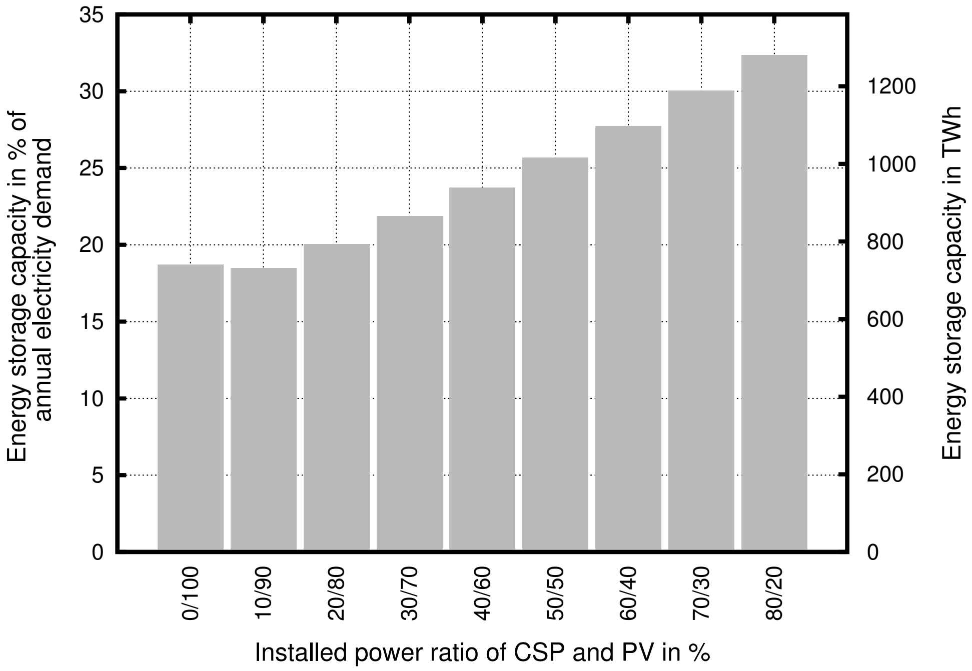
As CSP plants typically have a thermal storage to become more independent of the daily variations of solar radiation, they could be an option to PV power plants to reduce the required energy storage that balances the supply and demand of electricity. To investigate this while using the weather data of 2009, the 100 % PV power scenario for Europe was choosen and modified by substituting parts of the PV by CSP plants.

Except for a very small reduction of the required energy storage capacity for an electricity supply by 90 % PV and 10 % CSP plant capacities, the required storage capacity rises almost linear instead of decreasing (fig.: 5.27(a)). Starting from a required energy storage capacity of 18.7 % of Europe's annual electricity demand it reaches 32.3 % for an electricity supply by 80 % CSP and 20 % PV power plants. A further increas of CSP ratio was not possible as the suitable area reaches its limit.

Looking on the generated electricity, there is a small decrease to the PV power ratio of 60 % of the power plant capacity, before it rises again slightly for a higher ratio of the CSP plants. The fraction of electricity generated by CSP plants rises in an logarithmic way. Therefore only a ratio of 30 % CSP plants already make about 50 % of the electricity supply (fig.: 5.27(b)).

Due to the increased efficiency of CSP in contrast to PV power plants, the required power to be installed for the electricity supply declines exponentially with a rising ratio of CSP plants (fig.: 5.27(c)). So for a ratio of 60 % CSP plants, the required power plant capacity is reduced by as much as a half. In total, the installed power plant capacity for the region of Europe decreases from 1000 % of the annual mean required power to 475 %.

In summary, to substitute PV by CSP plants does not help to reduce the required energy storage capacity but the needed power plant capacity itself.



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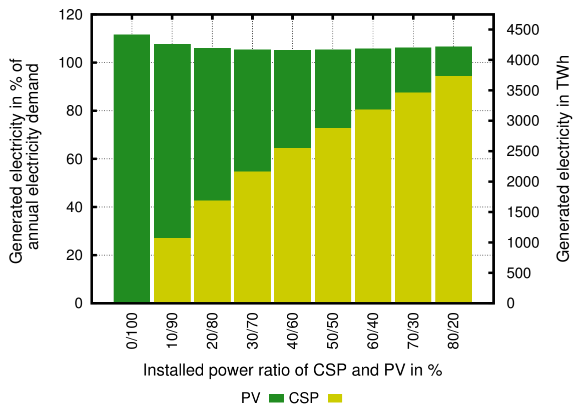

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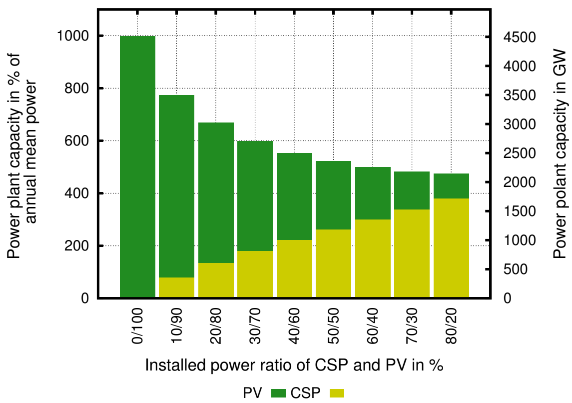


(c)

Figure 5.27.: Europe electricity supply of 3956 TWh/a by a varying ratio of only CSP and PV power plants installed and simulated with the weather of 2009. (a) Required energy storage capacity increasing from 18.7 % of the annual electricity demand for 100 % PV power to 32.3 % of the annual electricity demand for 80 % CSP and 20 % PV. A higher ratio of CSP was not possible as the required area to install CSP plants would exceed the limit of the MEET model. (b) Generated electricity by power plant type. Due to the higher full load hours of CSP plants, their electricity share rises fast with their capacity and at the 30 % power capacity scenario CSP plants already generate 50 % of the required electricity (c) Required power to be installed for the electricity supply. The required power plant capacity decreases fast from 1000 % of the annual mean required power for 100 % PV to 475 % of the annual mean power for 80 % CSP and 20 % PV power. This reduced capacity forces the increase of the energy storage capacity of (a) to compensate the seasonal variations.

6. Discussion of electricity supply scenarios

The results presented in section 5 will be discussed here. Also further investigations on possible consequences in terms of e.g. required area, energy storage plants or supply security for some of the presented electricity supply scenarios will be shown. Again, the focus for the detailed discussions is set to the model region of Europe.

Even if it could be a goal of a future electricity supply dominated by weather dependent renewable energies to reduce the required energy storage capacity to a minimum, the economic view plays a major role as well and typically dominate the decisions for a resulting power plant mix. Therefore an estimate of the influence on the cost for electricity is presented in this section in addition.

6.1. Rising energy storage needs for a transition to a renewable electricity supply

The discussion in this section is based on the results of the simulations presented in section 5.4 and 5.5. Scenarios of a transition from the European electricity supply system towards a supply by only wind and PV power have been investigated by using the MEET model. So the rising needs for energy storage capacities and the use of these capacities in the course of a year will be discussed as well as the options of realizing these capacities.

The transition from an electricity supply, based on fuel fired power plants to a supply by power plants using weather dependent renewable energies, leads to a strong increase in required energy storage capacities as presented in section 5.4. This is based on the fact, that most conventional power plants of today can be adjusted in their electricity generation to the demand (Weindorf, 2011). But power plants that use weather dependent energy sources as wind or solar energy, need additional energy storage systems to get the electricity generation and demand together.

Based on EURELECTRIC (2011), the current energy storage capacity of European pumped hydro power storage plants is about 2.5 TWh, which corresponds to 0.06 % of the annual electricity demand of the MEET model region of Europe. The simulation of the MEET model for the European electricity supply, using the power plant mix of 2007, did not require an energy storage. The already existing energy storage capacities of Europe have not been exceeded by the simulations until a power plant share between 50 % and 60 % of installed wind and PV power (fig.: 5.19). This could be explained on the one hand side, as the MEET model is based on the assumption of a perfect electricity grid that allows a balanced electricity supply all over the model region. On the other hand side one should not forget that, even in the 50 % wind and PV power scenario, only 26 % (fig.: 5.21 (b)) of the annual ectricity is generated by the non regulatable power plants. But the main reason for today's energy storage demand is based on economics, like giving the option to keep nuclear power plants running over low demand night times or to use temporal price differences on the electricity market.

The required energy storage capacity up to the scenario with a 50 % wind and PV power share is extremely low compared to the high share scenarios with an demand for storage capacities of about two orders of magnitude higher. The energy strong capacity increas up to 3.8 % (148.8 TWh) of the annual electricity demand is based on the fact that around the share of 50 % wind and PV power plants, their installed power capacity exceeds the maximum power demand of the model region (fig.: 5.21 (a)). So the chance that, in good weather conditions, these power plants generate more electricity than actually needed is given and rises with each increase of the installed wind and PV power plant capacity. So as not waste the energy, energy storage plants are required to balance the electricity generation and demand over the day or even over seasons. Only by increasing the installed wind and PV power plant capacity beyond 100 %, the resulting excess power reduces the required energy storage capacity again, but this effect will be discussed in section 6.2.4.

6.1.1. The relation between required energy storage power and capacity

Considering the power the energy storage would need to give to or to take from the electricity grid in the case of the 100 % share of wind and PV power plants to level out electricity generation and demand, the duration curve in fig.: 5.22 (a) provides an overview. Thus, the rated electricity generator power of the storage device is at about 110 % of the annual mean power demand and the rated power of the storage unit comes out with about 260 %. This ratio of about 1 kW : 2.4 kW for electricity generation and storing for the energy storage is based on the high amount of installed power plant capacity. For the 30 % wind and 70 % PV power scenarion, 663 % of the annual mean power demand is required to be installed (fig.: 5.2 (c)) and if they all operate well for the same time due to good weather conditions, the energy storage obviously will have to take a high power from the grid. Due to the different loads for storing energy and generating electricity, the time in which the energy storage is required as electricity supplier is about 62 % of the year. So the electricity supply benefit for a long time of some intensive peaks in electricity generation by the volatile wind and PV power.

6.1.2. The benefit of separating energy storage tasks into long and short time storage

As described in Götz (2013), it is of interest to separate the energy storage tasks to a Long Time Storage (LTS) and a Short Time Storage (STS) for an optimized use that considers their specific requirements. In this case the deviation of the energy storage systems was defined by the storage cycle time of maximum 24 h for the STS and storage cycle times exceeding this time were related to the LTS. Thus, for the 100 % wind and PV power scenario, Europe requires a capacity of 0.1% (4.1 TWh) of the annual electricity demand for the STS and 3.7% (146.2 TWh) for the LTS. The reason why their sum is slightly higher than the storage capacity of one single energy storage type (148.8 TWh) is simply based on the fact that their maximum filling levels are not necessarily reached at the same time (fig.: 5.23).

Investigating on the growth of the required energy storage capacity of STS and LTS for the rising share of wind and PV power plants, one could expect that, initially, the required STS capacity would rise followed by the required capacity of LTS. But in fact, even in the scenarios having a low share of wind and PV power, the required capacity of both storage types grow more or less in parallel (fig.: 5.24 (a)). Of course, at the beginning, the growth rate of the LTS is slightly reduced compared to the STS, but even at the beginning, storage cycle times of more than 24 h occur. On the other hand, the required storage capacity of the STS also rises up to the 100 % wind and PV power scenario. A major difference happens in the case of excess power plant capacities. While the required storage capacity of the LTS gets reduced by the excess capacity, the STS capacity stays uneffected (fig.: 5.24 (a)). So this excess capacity specially helps to reduce the seasonal deficites in the electricity supply, while the daly balancing needs specially triggerd by the behaviour of PV power and the day and night cycle of electricity demand, still remain.

Considering the total amount of energy that passes the LTS and STS during a year, this number is almost the same for both storage types once the share of wind and PV power plant capacity exceeds 60 % (fig.: 5.24 (b)). Even if the LTS has a much higher capacity, the STS compensates this easily as it is used much more often for these scenarios (fig.: 5.24 (c)). So for the 100 % wind and PV power scenario, the LTS mainly balances the seasonal differences and reaches just under three turn-overs of its storage capacity. In contrast, the STS that balances the daily fluctuations of electricity generation and demand, ends up with about 165 turn-overs of its storage capacitywhich means that on average, approximatly half its storage capacity gets used day by day.

Concluding the behaviour of LTS and STS, the deviation into these two energy storage systems allows an optimized use of different energy storage technologies[1] for their requirements. In the case of a STS it is important that the storage system has a high efficiency to reduce the energy losses while using the storage device as it will be used around 57 times more often than an LTS. For the LTS, a major point is the energy density to reduce the required space for the around 35 times higher capacities compared to the STS, that would be needed to be installed. So, as STS for example pumped hydro power storage plants, compressed air energy storage or battery systems would be a good choice and as LTS to generate hydrogen or methane and store this offers a good option because of an energy density about 100 times higher than the mentioned STS technologies (Götz, 2013).

6.1.3. Requirements for power plants during the energy supply transition to 100% wind and PV power for Europe

Regarding the full load hours of the power plant types for the transition towards an electricity supply by 100 % wind and PV power plants, the efficency of use reduces slightly for wind and PV power plants with their rising share as the best sites have been used first (fig.: 5.20). This effect is even stronger for

[1] For detailed informations on the energy storage technologies see Bünger et al. (2009), Götz (2013) or with focus on CAES systems Vardag (2010).

the wind than for the PV power, because the spacial differences in the wind power potential are much larger than for the PV power (fig.: 4.3 and 4.2). The simulated full load hours of bio power plants should not be seen as real, as the main effect results from an artefact of the whole-percent-numbers used for the setup of the power plant mix for the scenarios. So, the small share of only 2 % bio power in the begining lead to a reduction in only two steps for the 30 % and the 70 % wind and PV power scenario. For the other scenarios the in total rising power plant capacity that is needed to be installed even leads to a rising bio power plant capacity and thereby to a reduction of the full load hours.

Most interesting is the behaviour of the nuclear, coal and gas power plants. Up to an share of 30 % wind and PV power, the full load hours of the coal, and specially gas power plants get reduced to compensate the increased electricity generation by renewable energies. The nuclear power plants, having the highest priority to feed-in their electricity in contrast to coal and gas power plants, is superseded by the feed-in of wind and PV power plants after they reach a 30 % share of installed power capacity. From this point, the unflexible nuclear power plants get reduced in their full load hours from more than 8000 h to only 1300 h in the end. The coal power plants show the same trend but in a reduced way as their downtime is about four times less than from the nuclear power plants (tab.: 3.6). Only the gas power plants increase their full load hours from around 3000 h to 5000 h before they come out of the supply scenario. The given down time of only 3 houres and their low minimum load level of 18 % of the rated power allows the gas power plants to compensate the fluctuations in the electricity generation of the wind and PV power plants.

Aiming towards a 100 % electricity supply by wind and PV power plants, the in total power plant capacity required to be installed rises exponentially (fig.: 5.21 (a)). This is based on the accumulation of two effects. First, the wind and specially the PV power plants generate much less electricity per installed capacity during a year (compare full load hours fig.: 5.20) so that, for example, a share of 70 % of wind and PV power is needed to generate about 50 % of the required electricity (fig.: 5.21 (b)). Second, the rising share of wind and PV power also reduces the full load hours of the coal and nuclear power plants. Therefore the required power plant capacity rises from 170 % to 670 % of the annual mean power demand.

6.1.4. Feasibility of installing the required energy storage capacity in Europe

Coming to the feasibility of the required storage capacities, even the highest required capacity resulting from the 100 % wind and PV power scenario with its 3.8 % (148.8 TWh) of the annual electricity demand seems to be quite practicable for Europe. Thinking about pumped hydro power storage plants as the most developed large storage technology, the actual capacity of Europe, with about 2.5 TWh (EURELECTRIC, 2011), is more than enough for the begining of the transition of the electricity supply system. Regarding the expected potentials of Scandinavian pumped hydro power storage plants with 121.5 TWh storage capacity (Sterner et al., 2010), it shows that Europe should be able to manage the required storage capacity of 148.8 TWh for the 100 % scenario with this storage technology.

Thinking about a separation of the energy storage into STS and LTS systems, things become even easier. The required 4.1 TWh STS capacity for the 100 % scenario forces only an increase of Europe's pumped hydro power storage capacity by 40 %. Then the 146.2 TWh LTS capacity could be realised by storing the energy by generating hydrogen or methane and pumping it into underground gas cavernes. Estimating the required gas volume that would be needed to be stored by using the calorific value of hydrogen of 2.995 kWh/m^3 (normed[2]) or for methane with 9.968 kWh/m^3 (normed) and the efficency of modern gas power plants of 0.39 (Höflich et al., 2010), Europe would require to store 125.2·10^9 m^3 hydrogen or 37.6·10^9 methane as LTS. As underground gas storage facilities are already a common way of storing natural gas, it should be no problem to provide the required storage capacities. Even Germany had in 2012 about 22·10^9 m^3 of operating volume (Erdgasspeicherung, 2013) and Europe had approximately 175.5·10^9 m^3 already installed in 1999 (Sedlacek, 1999).

In fact the above mentioned gas storages are already in use, but in the case of a 100 % electricity supply by wind and solar power the need to store natural gas would be hardly reduced. Anyway, the estimation demonstrates that the required storage capacity is not a project of unrealistic size.
The feasibility of installing the required wind and PV power plants will be discussed in section 6.2 and the example for Germany can be found in section 6.4.

6.2. 100 % electricity supply by wind and PV power

As wind and solar power have the highest potentials and will play the major role in a renewable electricity supply (Heide et al., 2010; Vuuren et al., 2009), a special focus was set on this weather dependant energy sources and their effect on the requirements of energy storage capacities. Based on the results of section 5.1 and 5.2, the options for an electricity supply based on wind and PV power only will be discussed in this section. Therefore the dependency of required energy storage capacities on the mix of wind and PV power has been investigated as well as the effect of wind and PV power excess capacities. Regarding the analysis of multiple years of weather date, an estimation of the security of energy supply based on the available storage capacity will be given. Finally, a parametric equation coming from the fit-functions for the wind and PV mix and the excess capacity analysis has been constructed to describe the behaviour of required energy storage capacity over the whole range of options for the example of Europe.

6.2.1. Mixing wind and solar power

The influence on the required energy storage capacities due to mixing wind and PV power plants being discussed in this section are based on the simulations presented in section 5.1.

Especially in regions of higher degrees of latitude, where the availability of wind and solar power varies with the seasons, it might be of interest to mix these energy sources. As wind typically dominates the winter season and sunshine rises in its availability and intensity in the summer, the required energy

[2]The capacity of a m^3 gas is normed to standard pressure of 101,325 Pa and to standard temperature of 273.15 K.

storage capacity to balance the seasonal differences in electricity generation by wind and PV power can be reduced by installing a specific mix of power plant capacities.

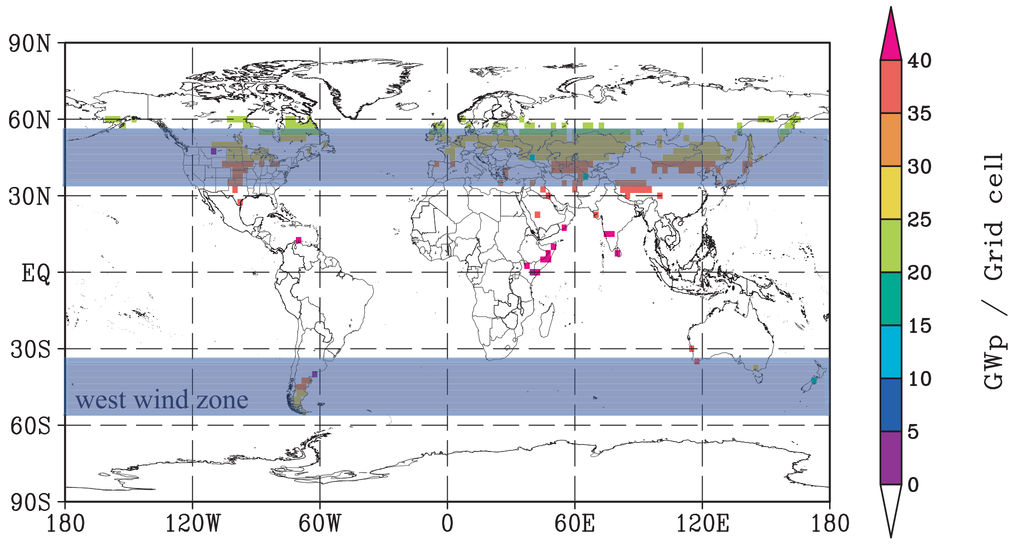
In the case of Europe, the required energy storage capacity is minimized for a mix of 30 % wind and 70 % PV power plants (fig.: 5.2 (a)). This can be explained as Europe fits almost perfectly into the west wind zone (fig.: 6.1 (a)) with its strong seasonal cycle of weather conditions. In this combination both power plant types generate about 50 % of the required electricity during a year (fig.: 5.2 (b)). So they compensate their seasonal variations as given in fig.: 5.1 (a) to (c). Of course to minimize the required energy storage capacity does not need to be the only criteria. The role of costs plays a major role beside the general feasability for planing a future electricty supply system, but this will be discussed in section 6.3.

Except for Europe and New Zealand, all other regions of the MEET model are passed by the 30th degree of latitude either in the northern or southern hemisphere. This region is known as the subtropical high pressure belt, where the air coming from the equator sinks down in the cycle of the Hadley cell and leads to almost cloud free and dry weather conditions. These conditions clearly favour the use of solar power and so the MEET model typically tries to use this regions for placing the PV power plants (fig.: 6.1 (b)). As these regions are much less sensitive to the annual cycle, the required energy storage capacity minimizing the supply scenarios of North America, Asia and Africa clearly tend to be of a higher or even 100 % ratio of PV power plants (fig.: 5.5 (a), 5.7 (a) and 5.8 (a)). In the cases of North America and Asia this even lead to the lowest required energy storage capacities relative to their annual electricity demand with almost 2 %.

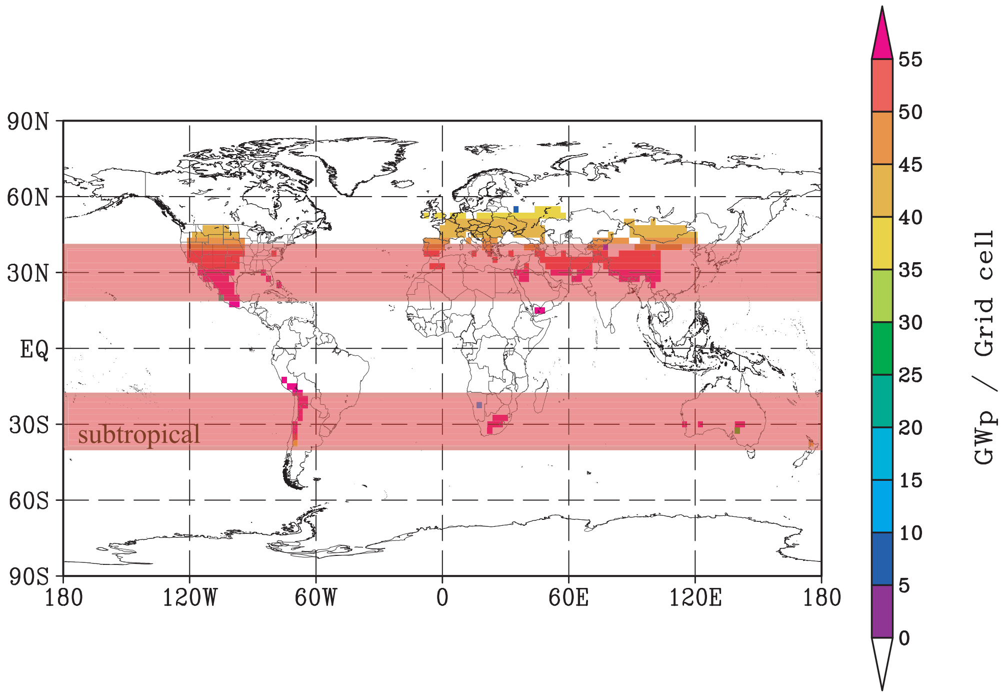
In the case of South America, the Andes offer a high potential for PV power as their height leads to increased solar irradiation combined with a reduced air temperature. Because of their large extension in a north-south-direction, the MEET model places a lot of PV power plants as well outside the subtropical high pressure belt, which again increases the seasonal variability. Therefore, a combination with wind power reduces the required energy storage capacity for this model region mostly at a ratio of 50 % wind and 50 % PV power plants (fig.: 5.4 (a)).

Regarding the results of the model regions of Australia and New Zealand, it should be mentioned that they might be less robust than the other regions. As the annual electricity demand of these regions are quite low compared to the other regions, just a few grid cells get used by power plants to supply the whole region (fig.: 6.1 (a) and (b)). Therefore the behaviour of electricity generation and required energy storage capacities is sensitive to the weather of these few grid cells. Australia is the only model region where the maximum of required energy storage capacity occurred not at one of the 100 % wind or PV supply scenarios but at 20 % wind and 80 % PV power (fig.: 5.3 (a)). Even if the PV power is placed along 30° latitude, the lowest required energy storage capacity on average is reached at a ratio of 50 % wind and 50 % PV power. Taking the variability of required energy storage capacity among the simulated years into account, the 100 % PV power scenario might perhaps be the best trade-off for this region.

Finally, one can conclude that, for all model regions, the in-total power plant capacity required to be installed rises in an exponential way with the ratio of PV power plants. This will be an important point once it comes to the influence of costs on the preferred power plant mix (section 6.3). On the other hand, the variation of annually generated electricity for PV power plants is only about the half that of the variations for wind power plants (fig.: 4.2 and 4.3). This leads to the fact that in almost all cases the standard deviation of the on-average required energy storage capacities rises with the ratio of wind power plants being installed.



(a)



(b)

Figure 6.1.: Distribution of installed wind and PV power plants on the MEET model grid cells having a resolution of 2.5° latitude and longitude. (a) Installed wind power capacities for a 100 % wind power supply of all MEET model regions. While Europe, having a high electricity demand compared to its land area, the wind power plants are installed to many grid cells, other regions show wide unused areas. In the very most cases the wind power plants can be found installed in the west wind zone. (b) Installed PV power capacities for a 100 % PV power supply of all MEET model regions. Again Europe shows a high density of used area but in general the favoured regions to install PV power plants can be found along the subtropical high pressure belt.

6.2.2. Security of electricity supply of Europe depending on the energy storage capacity

The calculations of the required energy storage capacity for an electricity supply based on wind and PV power presented in section 5.1 have been made by using weather data from the year 2000 to 2010. Therefore, the standard deviation of the on-average required energy storage capacity can be used to estimate the required energy storage capacity necessary to manage a certain amount of potentially possible years of weather conditions.

In the case of Europe the required energy storage capacities and their standard deviations given in fig.: 5.2 (a) have been used to calculate the 80 % (mean + 0.84σ), 90 % (mean + 1.28σ), 95 % (mean + 1.65σ), 99 % (mean + 2.33σ), 99.9 % (mean + 3.09σ) and 99.99 % (mean + 3.72σ) quantile of required energy storage capacities (fig.: 6.2). Due to the different standard deviations of the modelled electricity supply scenarios, the shape of the original courve is changing slightly, but the principal behavior keeps the same. As the variability of wind power scenarios is higher than the variability of PV power, the required energy storage capacity to guarantee the prefered quantile rises faster for the wind power dominated scenarios, but only for the 99.99 % security quantile, the required energy storage capacity of the 100 % wind power scenario exceeds the capacity of the 100 % PV power. The 30 % wind and 70 % PV power scenario is still the electricity supply requiring the lowest amount of energy storage capacities for all quantiles. In this case the 99.99 % quantile requires, in contrast to the simulated 50 % mean value, almost a doubling of the energy storage capacity from 3.8 % to 7.5 % of the annual electricity demand.

Finally, the choice of energy storage capacity will be an economic question since, for example, the security of the 99.99 % quantile would mean that only one in 10,000 years this storage capacity would not be sufficent but in almost all other years a part of this capacity will not be used. The option of installing energy storage capacities covering extreme high quantiles gets even more relative as the loss of a certain ammount of storage capacity typically does not need to lead to a total blackout as some power plants will always generate electricity. So, just a reduction by some consumers would be a typical impact instead of a total shut down. To illustrate this behaviour, the timeseries of the energy storage from the 30 % wind and 70 % PV power scenario has been choosen for the weather data of 2009. A reduction of the total energy storage capacity leads in this case to an deficit in spring time (fig.: 6.3). While the end time of the deficit period is always at the same point, from there the generated electricity gets enough to charge the energy storage in the long run, and the starting point gets even earlier with the reduced energy storage capacity. For the extreme case with only 50 % of energy storage capacity, which approximately correspond to the storage difference of the 99.99 % and the mean case the 50 % quantile , the whole period from the first deficit to the last takes 2811 h. This sounds a lot, but the time of real deficites in electricity supply is much shorter and takes in total 276 h.

For the worst time step at the 50 % energy storage capacity scenario, 90% of the current power demand could not be supplied. This only occures in a very few houres in total. In most cases, the power deficit is between 70 % and 30 % of the power demand, while deficits below 30 % again occur only very rarely

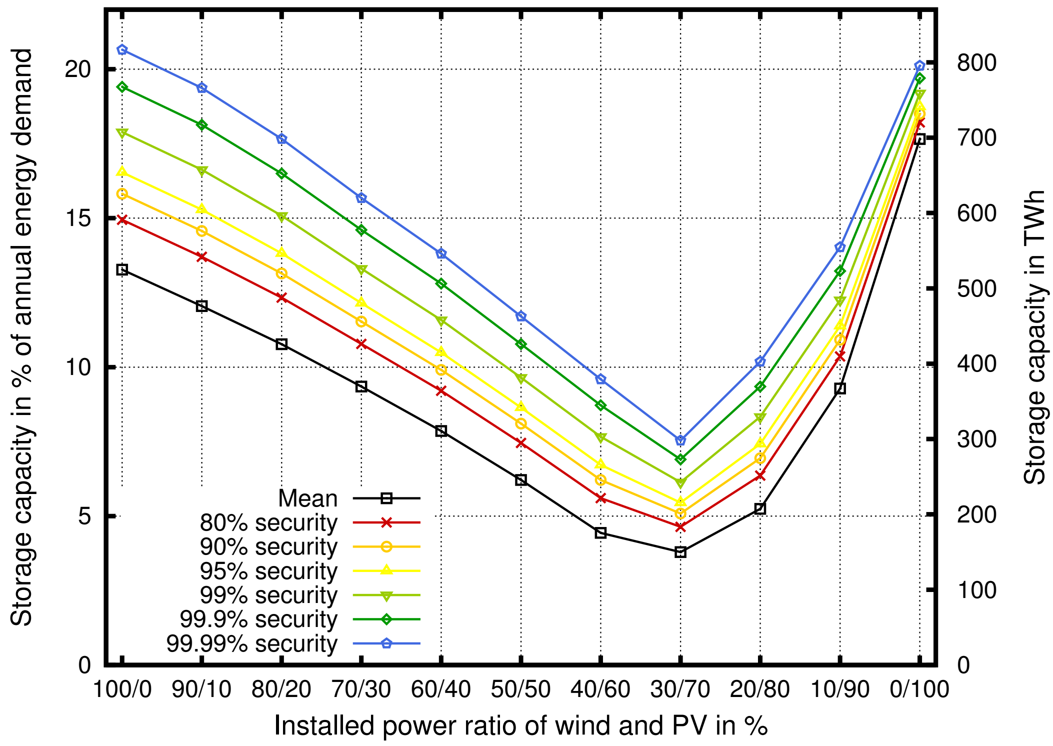


Figure 6.2.: Supply security for electricity supply of Europe (3956 TWh/a) for varying ratios of installed wind and PV power starting at the left with 100 % wind and 0 % PV power and going by 10 % steps to a 0 % wind and 100 % PV power scenario calculated by using weather data from 2000 to 2010. The black marks represent the mean required energy storage capacity of the years 2000 to 2010 and the coloured marks the required energy storage capacity that will be required to be sufficient for 80 % up to 99.99 % of all weather years. The security is based on the sigma range of the eleven simulated years (compare fig.: 5.2 (a)). Due to the higher variability for the wind power compared to the PV power scenarios, the required energy storage capacity for 100 % wind power exceed the storage capacity of the 100 % PV power scenario for the 99.99 % security.

(fig.: 6.4 (a)). The duration curves of the larger energy storage capacities get continiously reduced in the total time of deficits and the curves get even steeper. As the power demand varies in time and the duration curves of supply deficits have not been given only in per-cent of the current demand, but in GW as well (fig.: 6.4 (b)).

In principal, if the electricity generation or at least the long term trend could be forecast well enough, one could reduce the size of the power deficits by shifting a part of it to earlier times by shutting down some consumers in advance and thereby saving energy to compensate a part of the larger deficits. This could be of interest if, for example, some industries get special electricity contracts with reduced prices but with the option of taking them off the electricity grid in critical times.

The energy deficit in total is very low over the year. Even an Energy storage with just 80 % of the required capacity still does not lead to a deficit in electricity supply of one percent of the annual electricity demand (tab.: 6.1). The scenario with an energy storage of only 50 % actually leads to an electricity deficit of 1.79 %. Of cource in total this would be the electricity consumption of just under

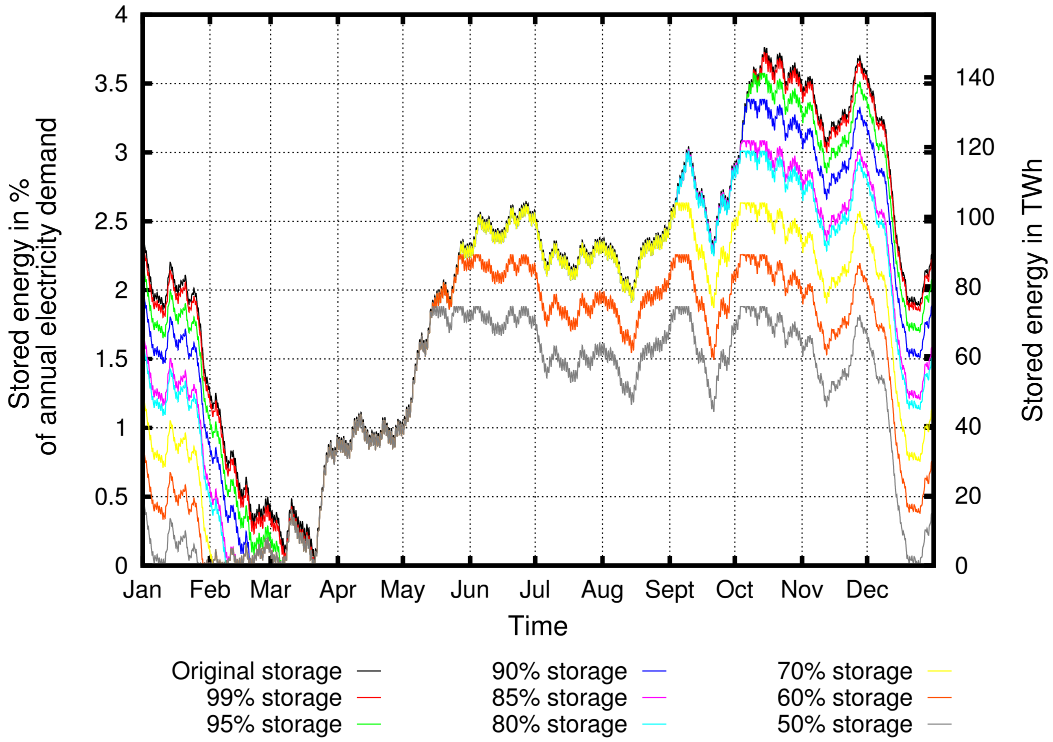


Figure 6.3.: Time series of stored energy for the 30 % wind and 70 % PV power scenario of Europe (3956 TWh/a) and the weather data of 2009. The black line represents the required energy storage capacity to pas the year without a deficit and the coloured lines represent energy storage capacities of 99 %, 95 %, 90 %, 85 %, 80 %, 70 %, 60 % and 50 % of the required storage capacity. The time in spring when the energy storage is empty increases with reduced energy storage capacity as it is not enough to compensate the seasonal variation in electricity supply and regarding autumn, the required energy can not be totally stored in the limited scenarios.

one week, but spreading this deficit over a longer period while the storage is operating (fig.: 6.2), even this should not be too critical as in thit case only some consumers would have to save electricity for this period instead of having a blackout at the end.

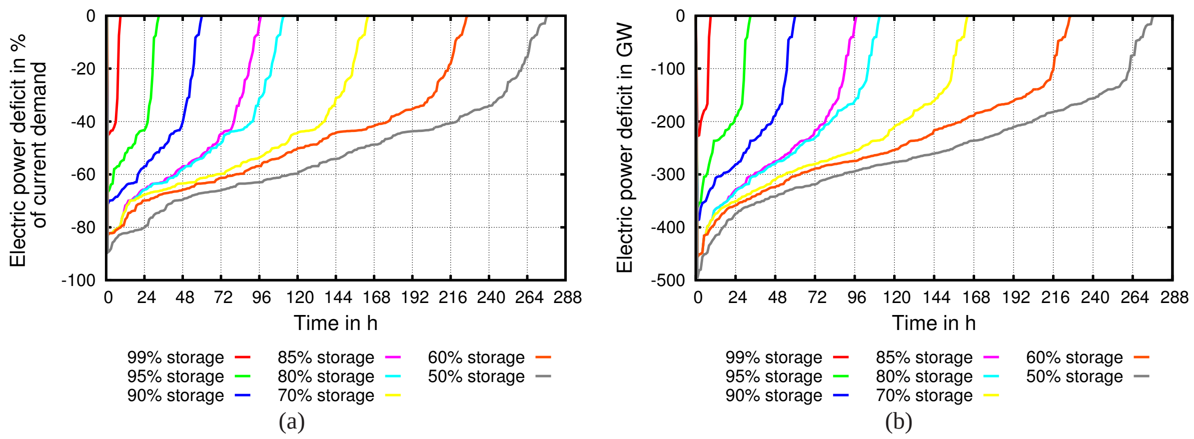


Figure 6.4.: Duration curves of deficits in electricity supply for reduced energy storage capacities given in fig.: 6.3 of the 30 % wind and 70 % PV power scenario of Europe (a) in % of the current power demand and (b) in GW. Even if the available energy storage capacity is only 50 % of the required capacity, a maximum of 276 h will be with a deficit in the electricity supply and there will be no time without any electricity, as the highest deficit is 89 % of the in this time required electric power.

Table 6.1.: Total electricity supply deficit due to reduced storage capacity for the 30 % wind and 70 % PV scenario without excess power plant capacity and an electricity demand of 3956 TWh/a of Europe. The reduced energy storage capacity for the scenarios is given in % of the energy storage capacity (3.8 % of the annual electricity demand) being required for a supply without a deficit.

Energy storage capacity in % of original required capacity	Electricity supply deficit in % of annual demand
99	0.04
95	0.18
90	0.37
85	0.65
80	0.72
70	1.08
60	1.43
50	1.79

6.2.3. The feasibility of installing the required wind and PV power plants in Europe

Coming to the feasibility of installing the required wind and PV power plant capacities, the MEET model already uses reliable amounts of area (section 6.1) for the placement of power plants. So wind power will not exceed 5 % of the area of the model regions and PV power will even stay below 0.6 %, which for both is totally within the range of mentioned by Bofinger et al. (2011) and Braun and Oehsen (2012).

In the case of Europe, the 100 % wind power scenario with its 2374 GW installed peak power would require 189,920 km^2 or about 1.87 % of the total area. The 100 % PV power scenario, requiring 4560 GW peak power would need 31,920 km^2 of PV panels or 0.3 % of Europe's surface area. In contrast, the 30 % wind and 70 % PV power scenario would make use of 90,847 km^2 or 0.89 % of this region. Obviously wind power requires much more area per installed power capacity than PV power. This is simply based on the spacing between wind turbines to reduce wake effects, but as long it is not a sellted area where people could be disturbed by cast shadows or noise, the area below the wind turbines could be used for other purposes like farming.

To get these area sizes for wind and PV power plants into context, just the infrastructure for traffic in Germany requires 5 % of the total surface (Statistisches Bundesamt, 2008) and in Europe about 5 % is built-up area (Eurostat, 2013). So beside the fact that the required areas for power plants are totally in range of assumed potential areas (Bofinger et al., 2011; Braun and Oehsen, 2012), their share would be, even for the 100 % wind power scenario, less then a half of other infrastructures like the mentioned transportation sector. The situation gets even more feasable, since in most cases the areas for wind and PV power could easily have a second use. So PV panels can be installed on existing infrastructures such as roofs, and the area under wind-farms is still suitable as fields. Regarding the share of fields on the area of Europe with 25 % (Eurostat, 2013), it would be no problem to place the wind turbines on land that is already in use.

6.2.4. The option of adding excess capacity

Installing excess power plant capacities to the least required wind and PV power plants is an efficient way of reducing the required energy storage capacities. This has been demonstrated in section 5.2 for the regions of the MEET model at their individual wind and PV power plant mix that requires the lowest energy storage capacities, and will be discussed below.

For all model regions the adding of excess power plant capacities lead to a reduction of the required energy storage capacity in the way of an exponential decline. So while starting at storage capacities of around 2 % of the annual required electricity demand up to 6 %, depending on the region, the required storage converges to capacities between 0.15 % and 0.4 %. In the case of Europe the 150 TWh (3.8 % of annual electricity demand) of required energy storage capacity could be reduced to about 17.8 TWh (0.45 % of annual electricity demand) for a 50 % excess capacity and converge to about 8 TWh (0.2 % of annual electricity demand). About 2.5 TWh of the required storage capacity already exists in Europe (EURELECTRIC, 2011). The strong exponential reduction due to excess capacity confirme the results for Europe by Heide et al. (2011), having a required energy storage capacity of 0.5 % of the annual electricity demand for a 50 % excess capacity but starting at higher value of 10 % of the annual electricity demand as required storage capacity for no excess capacity. A reason for the variation is discussed in section 6.2.5.

In most cases the reducing effect tends to become quite slow after an installed excess capacity of 10 % to 20 %. But up to this point the reduction of required energy storage capacity has already reached 50 % or even 75 % of the originally required capacity (fig.: 5.9 to 5.15). The strength of the reducing effect is not directly dependant on the ratio of wind and PV power plants but is simply a result of the combination of the regions characteristics. So for different regions being supplied by 90 % to 100 % PV power there are, as well, reduction rates having a large exponential parameter of 0.18 and regions having a small exponential parameter of 0.07. About the same spread can be found for the regions using only 50 % PV power for electricity supply.

The reason why even small amounts of excess capacity reach this large effect of reducing the required energy storage capacity is the dominating seasonal behaviour of the energy storage, in this thesis also called the long time storage (LTS) (section 5.5). Looking on the example of Europe with the 30 % wind and 70 % PV power scenario, the stored energy reaches its maximum during October and November (fig.: 5.23). From this point the stored energy declines to zero on the long run until April. The now additionally installed excess wind and PV power plants do not only compensate the electricity deficit in April, that would be fixed by making use of the energy storage, these powerplants also feed in electricity all the time and reduce there by the use and thereby the declinerate of the stored energy. As even a small amount of additional power plant capacity has about four months to reduce the demand of the energy storage, the effect on the storage capacity in total is large. This is the reason as well why the LTS shows the strong reductions while the STS is mainly unaffected by these excess capacities (fig.: 5.24 (a)). To compensate large deficits in power supply over the short intraday periods, one would require much more additional power plant capacity.

An additional effect of having excess power plant capacities installed is obviously to generate additional electricity over the year that is actually not required (tab.: 5.2). Depending on the excess scenario, the additional electricity could reach from 0.4 % up to 83.8 % of the annual electricity demand. The challenge is that this electricity is not continuously available over the year, but under the point of placing the additional power plants to compensate storage capacities, the excess electricity is free. So imagine for example the 10 % excess capacity scenario, a minimum of 12.5 % (56.4 GW) of annual mean power would be available for a quarter of the year, 6.2 % for half a year or 3 % for three quaters of the year (tab.: 5.3). This could be, for example, of interest to energy users in heavy industries to do some extra production or one could use it for the traffic sector in terms of electro mobility or methanisation.

Returning again to the point of the required area for the wind and PV power plants to be installed in Europe as discussed in section 6.2.1, even the 100 % excess capacity scenario of a 100 % supply by wind power the 3.7 % fraction of land use would still be smaller as the fraction of traffic infrastructure in Germany (Statistisches Bundesamt, 2008) and therefore absolutely feasible. But with a mix with PV power the number gets even smaller and a 100 % excess power plant capacity seems anyway not to be of real interest as discussed in section 6.3.

6.2.5. Combining the options of wind power, PV power and excess capacity

Combining section 6.2.1 and 6.2.4 one gets the main options that have influence on the required energy storage capacity for an electricity supply based on wind and PV power. Based on the fit-results of section 5.1 and 5.2, eq.: [6.2] has been formed to describe this field of options for the example of Europe.

Eq.: [5.1] of section 5.1 is now specified as function $C_{s(\mu)}$ and describes the required energy storage capacity in per-cent of the annual electricity demand in dependency on the ratio of installed wind and PV power plant capacity. Eq.: [5.3] form section 5.2 is named $C_{s(\varepsilon)}$, which is a function of the installed excess power plant capacity and describes as well the required energy storage capacity in percent of the annual electricity demand. The combination of these two expressions that define the required energy storage capacity to pass a cycle of one year without a deficit in energy storage, leads to:

$$C_{s(\mu,\varepsilon)} = C_{s(\mu)} \cdot \left(\frac{C_{s(\varepsilon)}}{C_{s(\varepsilon_0)}} \right) \qquad [6.1]$$

$C_{s(\mu,\varepsilon)}$ returns the required energy storage capacity in percent of the annual electricity demand of a region as a function of the ratio of PV power plant capacity $\mu \in [0,100]$ in % and the installed excess power plant capacity $\varepsilon \in [0,100]$ in % as well. $C_{s(\varepsilon_0)}$ represents the required energy storage capacity for no excess power plant capacity at the wind and PV power mix, where the model region specific fit has been made. So eq.: [6.1] is based on the simplification that the shape of the storage reduction due to excess capacities is not depedndent on μ the ratio of PV power. This might not represent the real behaviour in total, but as in section 6.2.4 discussed is the separation for the regions a good first step and will work well enough to get an idea about the total field of options to take influence on the required energy storage capacity.

For in the case of Europe, $C_{s(\mu)}$ came out as a polynomial of the order of four and, using the fit parameters for Europe, eq.: [6.1] can be written as

$$\begin{aligned} C_{s\_EU(\mu,\varepsilon)} \quad = \quad & \left(15.224 - 0.2537 \cdot \left(1+\frac{\mu}{10}\right) + 0.728 \cdot \left(1+\frac{\mu}{10}\right)^2 - 0.154 \cdot \left(1+\frac{\mu}{10}\right)^3 \right. \\ + \quad & \left. 0.01 \cdot \left(1+\frac{\mu}{10}\right)^4\right) \cdot \left(\frac{0.193 + 3.6 \cdot e^{-\varepsilon \cdot 0.094}}{3.793}\right). \end{aligned} \qquad [6.2]$$

So $C_{s\_EU(\mu,\varepsilon)}$ gives the required energy storage capacity for Europe for the range of 100 % wind to a 100 % electricity supply by PV power and an excess power capacity from 0 % to 100 %. If wanted, eq.: [6.1] could be adjusted for the other regions of the MEET model too.

Regarding the field of required energy storage capacities for Europe based on eq.: [6.2] (fig.: 6.5), the minimum required energy storage capacity occurs for a ratio of 30 % wind and 70 % PV power plant capacity. From this storage capacity of just under 4 % of the annual electricity demand of Europe, a strong reduction effect due to the excess capacity gets the required energy storage at already 40 % excess power to only about 0.3 % of the annual electricity demand. Changing the power plant mix towards more PV power, the required energy storage capacity rises quickly to 18 % and towards a higher ratio of wind power, a much slower increase of required storage capacity up to 13 % can be found. Reaching an excess

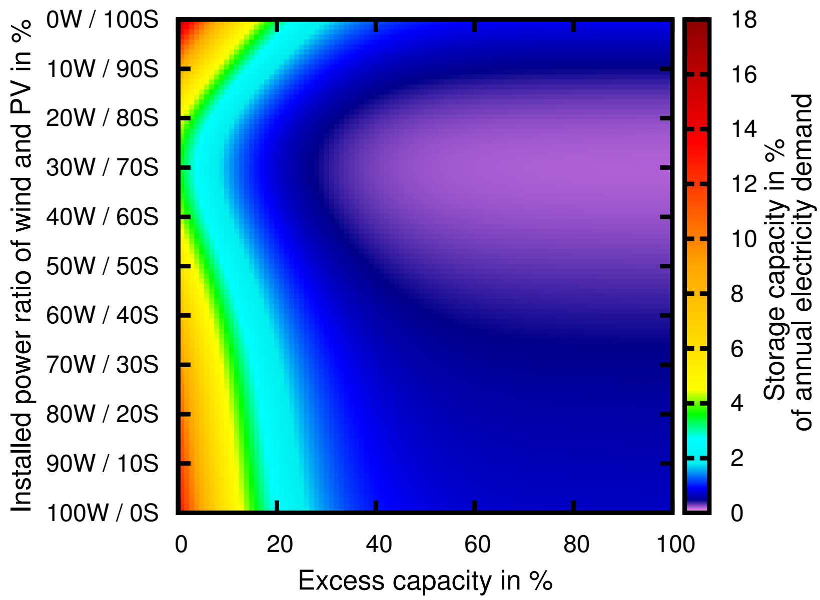


Figure 6.5.: Range of required energy storage capacities in % of annual electricity demand for individual mix of wind, PV and excess power for Europe by eq.: [6.2] based on the results of fig.: 5.2 (a) and fig.: 5.9. The lowes required energy storage capacity is in purple and belongs to about 0.2 % of the annual electricity demand. 1 % of the annual electricity demand can be translated into 87.6 h of annual average electricity demand.

power plant capacity of about 30 % it becomes more and more immaterial which power plant mix has been chosen as the storage capacity goes anyway under 1 % anyway of the annual electricity demand.

6.2.6. Comparing the behaviour of required energy storage capacity with other model results

A quite similar effect to fig.: 6.5 for the energy storage requirements for Europe could be shown by Heide et al. (2011), while using the model described in section 2.6 and in Heide et al. (2010). There a minimum required energy storage capacity of 10 % of the annual electricity demand has been found for a mix of 60 % electricity generated by wind and 40 % generated by PV power plants (Heide et al., 2011). This ratio is quite close to the 30 % wind and 70 % PV power scenario presented in this thesis, as between a ratio of 30 % to 40 % wind power; the generated electricity by wind power also makes around 60 % of the in-total generated electricity (fig.: 5.2 (b)).

The major reason why the minimum energy storage capacity discussed in this thesis, with its 3.8 % of the electricity demand, is approximatley 60 % smaller than the 10 % storage capacity given in Heide et al. (2011) is the fact that they did the simulations continously for eight years from 2000 to 2007. So in this case the energy storage even compensates variations among multiple years which leads to a much higher storage demand than to compensate as maximum the annual seasonal variations. In the case of Heide et al. (2011) this leads to the point that about 40 % of the mentioned energy storage capacity only get used in two of the eight years for a period of some weeks. Looking for the maximum instead of the averaged required energy storage capacity simulated by the MEET model for the years 2000 to 2007, the required storage capacity of 6 % (fig.: 5.2 (a)) in 2002 gets at least closer to the capacity required ine Heide et al. (2011) and even represents the 60 % of the energy storage simulated by Heide et al. (2011) that almost get used each year.

Regarding the extreme values of required energy storage capacities, Heide et al. (2011) shows quite similar results with about 20 % capacity for the wind or PV power only scenarios and for excess power plant capacities, the required storage decreases as well exponentially and gets below 0.5 % of the electricity demand for excess capacities of 50 % and more.

At the end, even using a different approach, the options to reduce the required energy storage capacity came out as similar which confirms the results. But finally, when it comes to reality, the economic view about the resulting costs for electricity will play a very important part too and sometimes totally change the options compared to fig.: 6.5. So this important point will be discussed in section 6.3.

6.3. The influence of costs on the power plant mix and excess capacity

Based on the results of section 5.1, 5.2 and 6.2 for an electricity supply by 100 % wind and PV power plants, the cost of this electricity generation will be estimated in the following as the example for Europe. Therefore, the focus is set to the influence of different energy storage costs and the changes to the electricity supply system while minimizing the costs instead of the energy storage capacities.

The generalized way of describing the spendings per unit of electricity is given by

$$S_{(\mu,\varepsilon)} = \frac{1}{100} \cdot \left(C_{s(\mu,\varepsilon)} \cdot S_s + \frac{C_{PV(\mu,\varepsilon)}}{8760} \cdot S_{PV} + \frac{C_{w(\mu,\varepsilon)}}{8760} \cdot S_w \right). \qquad [6.3]$$

So it is the amount of required energy storage capacities $C_{s(\mu,\varepsilon)}$ known from eq.: [6.1] times the annual spendings per storage capacity S_s plus the amount of PV and wind power plant capacities $C_{PV(\mu,\varepsilon)}$ and $C_{w(\mu,\varepsilon)}$ divided by the hours of a year[3] times the individual annual spendings S_{PV} and S_w per capacity. As the storage capacity is given as a percentage of the annual electricity demand and the power plant capacities as a percentage of the annual mean required power, an additional factor of $\frac{1}{100}$ is needed to get the total spending per unit of electricity supply.

In fact eq.: [6.3] dose not consider any additional costs like operating costs. As these power plants do not require any fuel, these utilisation dependent costs are quite small compared to the investment costs and are ignored in the following estimates of electricity prices.

Coming to the estimation of spending for electricity of Europe $S_{EU(\mu,\varepsilon)}$ in EUR / kWh for a supply by only wind and PV power, the required energy storage capacity as a function of the PV power ratio μ and the excess power plant capacity ε is given by eq.: [6.2] as $C_{s\_EU(\mu,\varepsilon)}$. The required power plant capacities

[3] This number of hours found from the mean annual power divided by the annual required electric energy.

in percent of the annual mean required electric power can be defined for Europe by the fit function given in section 5.1 fig.: 5.2 (c) as

$$C_{PV\_EU(\mu,\varepsilon)} = 487.774 + 9.816 \cdot e^{\left(1+\frac{\mu}{10}\right)\cdot 0.356} \cdot \left(1 + \frac{\varepsilon}{100}\right) \cdot \frac{\mu}{100} \qquad [6.4]$$

and

$$C_{w\_EU(\mu,\varepsilon)} = 487.774 + 9.816 \cdot e^{\left(1+\frac{\mu}{10}\right)\cdot 0.356} \cdot \left(1 + \frac{\varepsilon}{100}\right) \cdot \left(1 - \frac{\mu}{100}\right). \qquad [6.5]$$

The ratio of PV power $\mu \in [0,100]$ and the installed excess power plant capacity $\varepsilon \in [0,100]$ have to be inserted as percent values.

Getting the equations [6.2], [6.4] and [6.5] into eq.: [6.3], the spendings in EUR / kWh for Europe $S_{EU(\mu,\varepsilon)}$ can be calculated by

$$\begin{aligned} S_{EU(\mu,\varepsilon)} &= \frac{1}{100} \cdot \Bigg[\Bigg(15.224 - 0.2537 \cdot \left(1+\frac{\mu}{10}\right) + 0.728 \cdot \left(1+\frac{\mu}{10}\right)^2 - 0.154 \cdot \left(1+\frac{\mu}{10}\right)^3 \\ &+ 0.01 \cdot \left(1+\frac{\mu}{10}\right)^4\Bigg) \cdot \left(\frac{0.193 + 3.6 \cdot e^{-\varepsilon \cdot 0.094}}{3.793}\right) \cdot S_s \\ &+ \left(487.774 + 9.816 \cdot e^{\left(1+\frac{\mu}{10}\right)\cdot 0.356} \cdot \left(1+\frac{\varepsilon}{100}\right) \cdot \frac{\mu}{100}\right) \cdot \frac{S_{PV}}{8760} \\ &+ \left(487.774 + 9.816 \cdot e^{\left(1+\frac{\mu}{10}\right)\cdot 0.356} \cdot \left(1+\frac{\varepsilon}{100}\right) \cdot \left(1-\frac{\mu}{100}\right)\right) \cdot \frac{S_w}{8760}\Bigg]. \end{aligned} \qquad [6.6]$$

The parameters for the annual spendings S_s, S_w and S_{PV} for the storage, wind and PV capacities can be calculated by making use of the Net Present Value which is defined as

$$NPV = \sum_{t=1}^{T} \frac{S_t}{(1+i)^t} - I. \qquad [6.7]$$

The NPV allows to discount cash flows to their present value while taking inflation into account and is a standard tool of investment analysis. In this case I represents the investment into an energy storage, wind or PV plant. S_t is the cash flow or spending in each year that comes from selling the electricity, T stands for the number of years the plant will be able to operate and i is the discount rate which is set to a standard value of 0.06, as for example, in Faulstich et al. (2011) for the calculations of investments in renewable energies.

As the resulting electricity price should not be biased by individual profits of investors, the NPV is set to zero. Assuming now a constant electricity price over time, the cash flows S_t have to be constant, so eq.: [6.7] can be written as

$$S = I \cdot \frac{(1+i)^T \cdot i}{(1+i)^T - 1}. \qquad [6.8]$$

Now S represents the annual cash flow or the spending that is required to get back the investment into a storage, wind or PV plant without making any profits or deficits. Using estimated intermediate future prices for wind and PV power by Blesl and Fahl (2012) for the year 2030, the annual required spendings

S_s, S_{PV} and S_w per plant unit can be calculated by using eq.: [6.8] (tab.: 6.2 and 6.3). Because the costs for energy storage capacity cover a large range, from approximately some 100 EUR to less then 1 EUR per kWh of storage capacity, depending on the technology and the environmental boundary conditions (Vardag, 2010), a set of five storage cost scenarios has been assumed in tab. 6.3 as well.

Table 6.2.: Assumed costs of power plants (Blesl and Fahl, 2012) required for eq.: [6.6].

Plant	Life time [a]	Investment costs [EUR / kW]	Fixed costs [EUR / (kW a)]	Required annual cash flow [(EUR kW) / a]
Wind power	20	1050	50	91.54 + 50
PV power	25	1450	33	113.43 + 33

Table 6.3.: Assumed costs of energy storage (Vardag, 2010) required for eq.: [6.6].

Plant	Life time [a]	Investment costs [EUR / kWh]	Required annual cash flow [(EUR kWh) / a]	Technology example
Energy storage 1	40	1	0.06646	cheap hydrogen and methane storage
Energy storage 2	40	10	0.66462	hydrogen and methane storage
Energy storage 3	40	50	3.32308	CAES and pumped hydro power storage
Energy storage 4	40	100	6.64615	CAES, pumped hydro power storage and batteries
Energy storage 5	40	150	9.96923	expensive pumped hydro power storage and some batteries

Getting the required annual cash flows of tab.: 6.2 and 6.3 for the parameters S_s, S_{PV} and S_w into eq.: [6.6], one can calculate the price a consumer has to pay for electricity in EUR per kWh to finance an electricity supply system of energy storage capacities, wind and PV power plants. Additional costs like profits, electricity grid or taxation are not included in the spendings presented below. In Germany for example, the spendings for this part of electricity providing made about 28.9 % of the total electricity price for households in 2013 (Lange, 2014).

Table 6.4.: Minimum price for electricity for Europe at varying energy storage capacity costs based on eq.: [6.6] being plotted in fig.: 6.6 (a) and (b).

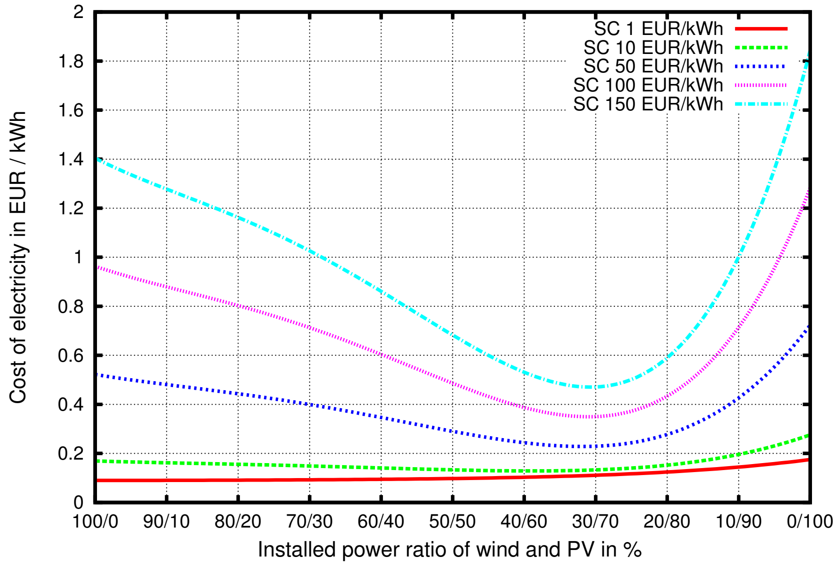
Scenario	Storage investment costs [EUR / kWh]	lowest electricity price [EUR / kWh]	Power plant setup
Excess power 0 %	1	0.09	100 % wind 0 % PV power
Excess power 0 %	10	0.13	39 % wind 61 % PV power
Excess power 0 %	50	0.23	32 % wind 68 % PV power
Excess power 0 %	100	0.35	31 % wind 69 % PV power
Excess power 0 %	150	0.47	30 % wind 70 % PV power
30 % wind 70 % PV power	1	0.11	Excess power 0 %
30 % wind 70 % PV power	10	0.13	Excess power 7 %
30 % wind 70 % PV power	50	0.15	Excess power 20 %
30 % wind 70 % PV power	100	0.17	Excess power 31 %
30 % wind 70 % PV power	150	0.18	Excess power 36 %

6.3.1. Electricity cost for Europe for a varying ratio of wind and PV power plant capacity

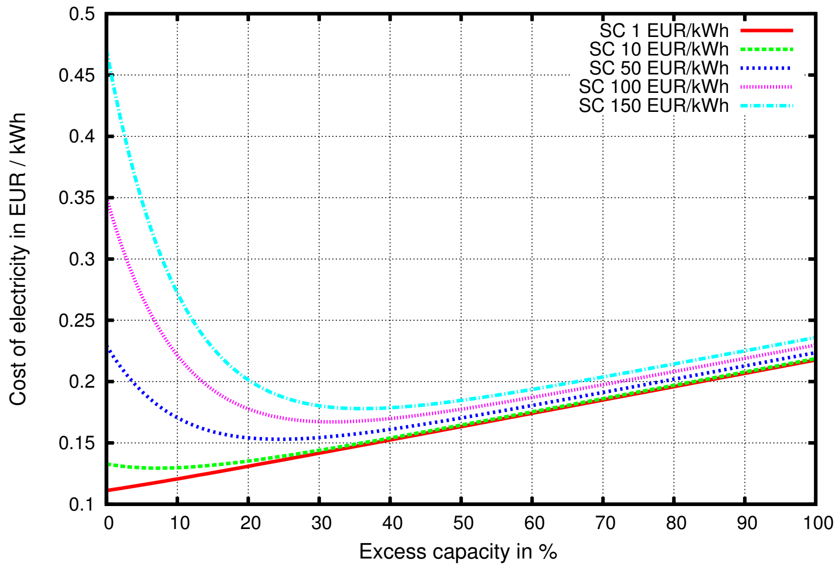
Looking at the behaviour of electricity prices in Europe for a mix of wind and PV power plants without excess capacities ($\varepsilon = 0$) and the influence of the costs of installing energy storage capacities (fig.: 6.6 (a)), the price varies from 0.09 EUR / kWh up to 1.84 EUR / kWh. In the case of very low energy storage costs of 1 EUR / kWh, the amount of required energy storage capacities is of a minor role and the lowest electricity price of 0.09 EUR / kWh occurs for a 100 % wind power supply. For rising energy storage costs, the influence of reducing the required energy storage capacity by developing the ratio of PV power plants becomes increasingly interesting (fig.: 6.6 (a) and tab.: 6.4). So the effects favouring a high ratio of wind power capacities is that the cost of them are lower than the cost of PV power capacities and partickularly the fact that with an increase of PV power, the in-total required power plant capacity rises quite strongly (fig.: 5.2 (c)). These effects favouring wind power capacity get counter by the effect of reducing the required energy storage capacity coming closer to an 30 % wind and 70 % PV power mix, which get even more interesting with rising storage costs. So for the 150 EUR / kWh, the storage costs dominate and thereby force the final power plant mix of 30 % wind and 70 % PV power (fig.: 6.6 (a) and tab.: 6.4).

6.3.2. Electricity cost for Europe considering excess power plant capacity

For the case of the fixed power plant ratio with 30 % wind and 70 % PV power plant capacity ($\mu = 70$), storage capacity costs do have a large impact too and lead to electricity costs from 0.11 EUR / kWh to 0.47 EUR / kWh (fig.: 6.6 (b) and tab.: 6.4). In contrast to the scenario without excess capacity, there is no final point to minimize electricity costs for rising storage capacity costs. Therefore, the optimal excess power plant capacity will still rise with increased energy storage costs (fig.: 6.6 (b)). As the dependence of storage capacity on the excess power is described by an exponential decrease (fig.: 5.9), the cost of minimizing excess power plant capacity will become harder to reach with rising storage costs.



(a)



(b)

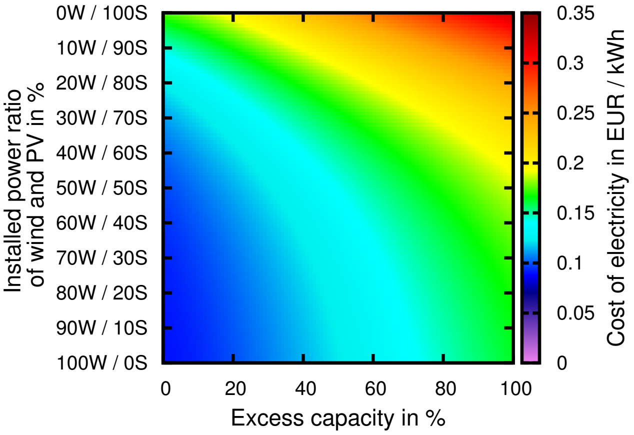
Figure 6.6.: Cost of electricity in EUR per kWh for Europe based on wind and PV power based on eq: [6.6] and storage investment costs of 1, 10, 50, 100 and 150 EUR/kWh. (a) Cost of electricity for varying ratio of wind and PV power at zero excess power. For the cheapest energy storage investment costs, the system is dominated by the power plant cost and tend thereby to the cheaper wind power plants. For rising energy storage investment cost it becomes more interesting to install the power plant mix requiring the lowest energy storage capacity (fig.: 5.2). (b) Cost of electricity for varying excess power plant capacity at 30 % wind and 70 % PV power ratio. The optimum excess power to be installed rises for increased energy storage investment costs. (For minimum of the curves see tab.: 6.4.)

6.3.3. Electricity cost for Europe for wind, PV and excess power capacity

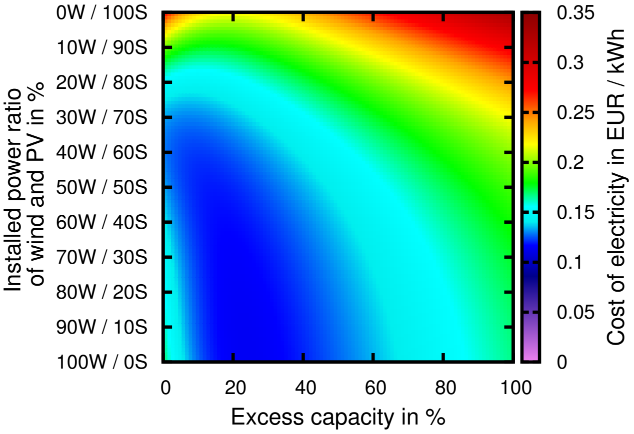
Allowing the variation of power plant mix and excess capacity at eq.: [6.6], one gets the impression that the full range of options will influence the electricity costs (fig.: 6.7). As costs for energy storage capacities, again 1, 10, 50, 100 and 150 EUR / kWh have been chosen to cover the range from relatively expensive storage capacities as large scale battery systems, pumped hydro power and CAES down to hydrogen or methane storage (Vardag, 2010).

In the case where building energy storage capacities is quite cheap with 1 EUR / kWh, again there is no reason to build more power plant capacities as the minimum required. Thus non-excess power high wind power scenarios give the lowest costs for electricity and a high ratio of PV power and additional excess power lead to the highest prices (fig.: 6.7 (a)).

Already at a price of 10 EUR / kWh of energy storage capacity the option of installing additional excess capacity becomes of interest and increases with rising storage cost (fig.: 6.7 (a) - (e)). Between storage costs of 10 EUR / kWh and 50 EUR / kWh, the highest costs of electricity change from the side of installing maximum excess capacity to the side installing no excess capacity. Thereby, excess capacities of about 10 % and above, depending on the ratio of wind and PV power, reach the lowest electricity costs. Finally the option of excess capacity does not only reduce the electricity cost but also allows a wider range of mixing wind and PV power plant capacities while ending at the same cost for electricity.


0W / 100S
10W / 90S
20W / 80S
30W / 70S
40W / 60S
50W / 50S
60W / 40S
70W / 30S
80W / 20S
90W / 10S
100W / 0S
Installed power ratio of wind and PV in %
0
20
40
60
80
100
Excess capacity in %
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Cost of electricity in EUR / kWh

(a)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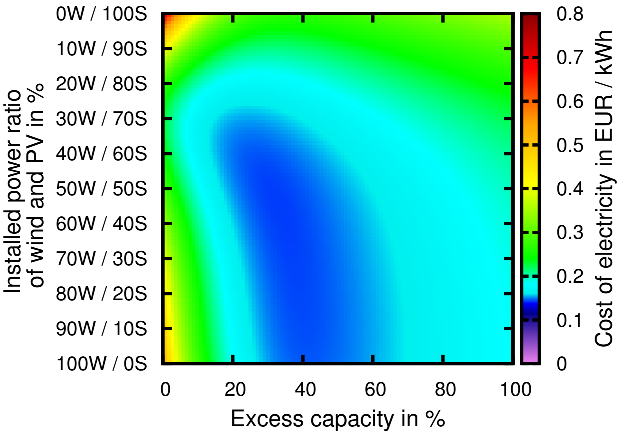
70W / 30S
80W / 20S
90W / 10S
100W / 0S
Installed power ratio of wind and PV in %
0
20
40
60
80
100
Excess capacity in %
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Cost of electricity in EUR / kWh

(b)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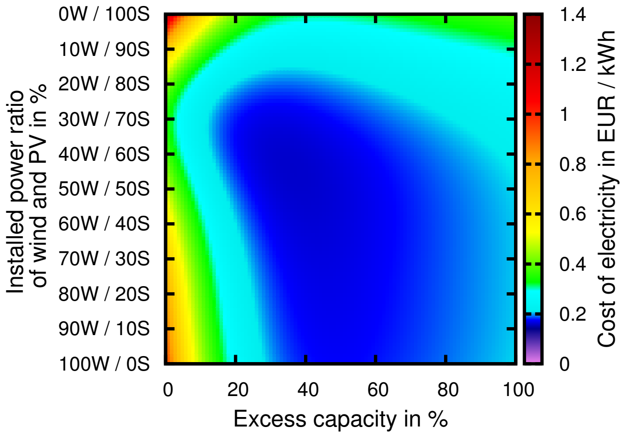
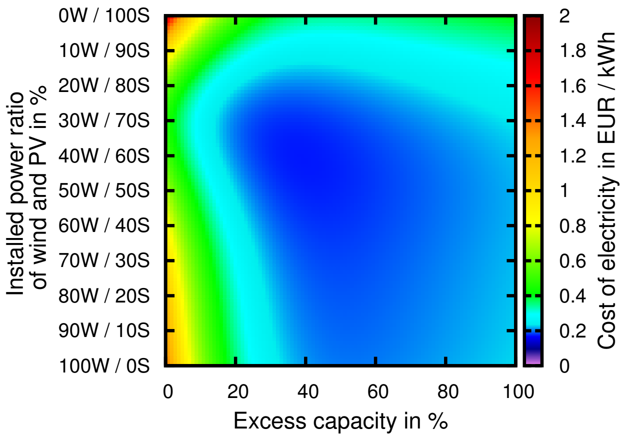
40W / 60S
50W / 50S
60W / 40S
70W / 30S
80W / 20S
90W / 10S
100W / 0S
Installed power ratio of wind and PV in %
0
20
40
60
80
100
Excess capacity in %
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cost of electricity in EUR / kWh

(c)



(d)



(e)

Figure 6.7.: Overview of the cost of electricity in EUR / kWh for a varying ratio of wind, PV and excess power being installed for Europe's electricity supply at energy storage capacity costs of (a) 1 EUR / kWh, (b) 10 EUR / kWh, (c) 50 EUR / kWh, (d) 100 EUR / kWh and (e) 150 EUR / kWh based on eq: [6.6]. For rising energy storage investment cost, the cheap electricity costs in the blue coloured zone move to a higher installed excess power plant capacity and an increased mixing of wind and PV power plant capacity.

Depending on the final cost of electricity storage capacities the minimum cost of electricity for a 100 % wind and PV power based electricity supply of Europe turned out between just under 0.1 EUR / kWh and up to about 0.2 EUR / kWh. Of course, looking for the worst case even 2 EUR / kWh forms the upper limit of the range for the given scenarios. Getting these costs for electricity into relation, Germanys households paid about 0.085 EUR / kWh in 2013 and, including all taxes and electricity grid costs, the price for electricity was 0.2938 EUR / kWh in total (Lange, 2014). So even for these 100 % wind and PV power scenarios and, ignoring additional renewable energy using power plants like biomass, CSP, ocean or hydro power plants and the highest assumed storage capacity costs of 150 EUR / kWh, the cost of electricity remains below a doubeling of today's electricity costs. Facing rising fuel costs of gas, coal and nuclear power plants, the dependency on the import of these fuels and external costs of the current electricity supply such as air polution, climate change damages or nuclear waste, the discussed costs of electricity seem absolutely in feasable. Last but not least, as taxes involve about 23 % of the electricity price in Germany and additional charges another 26 %, there is still space for the government to adjust the total price of electricity, specially as the afore mentioned externalise costs will be gone in a 100 % renewable electricity supply.

Finally the discussed dependency of electricity costs in eq.: [6.3] which could be arranged for any region of the MEET model and specially the presented behaviour of Europe's electricity costs at eq.: [6.6] could be used to improve the simulation of renewable energies in economic models like GREET, RICE or any other model that has a time resolution of only one year.

6.4. The effect of supply grid size for the example of Europe and Germany

In section 5.3 the required energy storage capacity has been investigated for the region of Germany. Comparing these results to those of Europe, the effect of the available size of an interconnected region on the electricity supply by wind and solar power will be worked out in the following.

Germany only accounts for about 3.5 % of the area of Europe. Its dimension from north to south is in the same order as a typical low pressure system (Kraus, 2004). Thus, it is possible that the whole region is under the influence of the same weather conditions, while a continental size region as Europe will always have a variety of wind, clouds and sunshine. Germany, which lies in the center of Europe with respect to the north south dimension, is located in the west wind zone and has thereby similar wind and PV power options as Europe. Therefore also the behaviour of the required energy storage capacity for a varying ratio of wind and PV power plant capacities is very similar for Germany and Europe (fig.: 5.17 (a)). In almost all cases the required energy storage capacity, relative to the electricity demand of the region, is higher for Germany than for Europe. Especially at the minimum they differ by a factor of about 2.2. While Germany requires a minimum energy storage capacity of 4.45 % (28.4 TWh) of the annual electricity demand (639.1 TWh in 2008 BP (2009)), Europe required only 2.01 % at the mix of 40 % wind and 60 % PV power for the weather data of 2009. Going to scenarios clearly dominated by either wind or PV power, the difference in the required storage capacity reduces to only a view percent.

In general Germany tend to favour wind power as for the 50 % to 80 % wind power scenarios, Germanys required energy storage is closest to the storage of Europe.

6.4.1. Feasibility of required energy storage capacity for Germany

The required 28.4 TWh storage capacity for Germany can be confirmed by the study of Nitsch et al. (2010a), where a range of 20 TWh to 40 TWh is given. In fact, the number to large to manage, regarding the existing capacity of pumped hydro power storage in Germany with about 39 GWh (EURELECTRIC, 2011). It seems not realistic to increase this capacity by a factor of more than 700 to fulfill the storage needs. Therefore additional options of storing energy will be required, if Germany wants to be independent. CAES systems might be an useful storage system and regarding the option of using hydrogen or methane as energy storage, the capacity of 28.4 TWh will not be problematical for Germany as today's existing gas-infrastructure of Germany could already provide 120 TWh of storage capacity when using methane (Sterner et al., 2011).

6.4.2. Required area to install wind and PV power in Germany

Regarding the required power plant capacities relative to the annual mean power demand of the region, Germany again performs worse compared to the larger area of Europe. This is based on the fact, that Europe offers much better wind sites such as Scotland or the enlarged coast lines, but also PV sites such as the Mediterranean region (fig.: 4.2 and 4.3). Therefore Germany requires 630 % of annual mean power in the best case and 1046 % in the worst case as power plant capacity, depending on the ratio of wind and PV power. In contrast, the required power plant capacity for Europe reaches from 491 % to 998 % of the annual mean power, for best and worst case scenario.

Due to the higher electricity demand per area and the reduced utilization of wind and PV power in Germany, the power plants require a higher share of the total area. 100 % wind power supply would require 11 % (39,288 km^2) of Germanys area compared to the 1.87 % for Europe. This ist not only a very high difference in required surface area of the model region, but also a critical value for Germany at all. Bofinger et al. (2011) worked out a share of 8 % of Germany's area suitable for wind power without any restrictions. In the 100 % PV power scenario, Germany would need 1.5 %(5340 km^2) of its area in contrast to the 0.3 % in the case of Europe. This is above the estimated available area for PV power of 0.8 % (Braun and Oehsen, 2012). For the 40 % wind and 60 % PV ratio, 5.1 % (18,390 km^2) of Germany would be required for electricity supply. In this case both, wind power with 4.5 % required area and PV power with 0.6 % do not exceed the maximally usable area.

As the power plants require a much higher relative share of the area in the case of Germany as for Europe, the decision of installing additional excess capacities to reduce the required energy storage capacity might be more critical. Also the exponential reduction of the required energy storage capacity due to excess capacity came out as less intensive as for Europe. The parameter of the exponent is 0.057 for Germany instead of 0.094 for Europe. Nevertheless, even 10 % excess capacity lead to a reduction of the required energy storage capacity from 4.45 % to 2.7 % (fig.: 5.18 and 5.9) of the annual electricity demand of Germany for the power plant ratio of 40 % wind and 60 % PV power.

In summary one can say, that the electricity supply of Germany by only wind and PV power is feasible with respect to the required area and the required energy storage capacities, but an enlarged electricity grid, interconnecting Europe has many positive effects due to averaging out of weather fluctuations and due to the sites outside of Germany having higher energy potentials. Therefore the required energy storage and power plant capacities can be significantly reduced. Finally it will be a question of economy whether it is worth to invest into a powerful electricity supply, dealing with the increased capacity requirements of single country or using other options.

6.5. Additional options for electricity supply and energy storage

In the sections above, the range of options and dependencies for an electricity supply based on wind and PV power were discussed with a focus on the requirements for energy storage capacities. As wind and solar power offer the largest potentials for electricity supply by renewable energies (Heide et al., 2010), the investigated behaviour is fundamental for the planning of a desirable power plant mix, excess capacities and required energy storage capacities. This section will now present some additional options to improve an electricity supply system.

Adding any kind of full controllable and weather independent power plant, such as bio power, geothermal power or hydro power to the weather dependent wind and PV power plants, will increase the flexibility in electricity generation. This allows a reduction of the required energy storage capacities just as decreasing the share of wind and PV power plant given in fig.: 5.19 towards an higher share of controllable power plants. But one should keep in mind, that the potentials of this controllable renewable power plants are significant smaller than these for wind and solar power (Moomaw et al., 2011).

Another option in wind power to increase the utilisation of wind power plants has been investigated by using the MEET model (section 5.6). The reduction of the generator power of the wind power plants (van der Hoeven, 2013) reduces the required energy storage capacity. When halving the generator power, the full load hours of the wind power plants rise by 40 % to 60 % on average depending on the scenario and the required energy storage capacity decreases by about 20 % for the 100 % wind power scenario and by 30 % for the 30 % wind and 70 % PV power ratio scenario. This measure increases the availability of wind power. Never the less it is still dominated by the seasonal variation and thereby the reduction of the required energy storage capacity remains high compared to the strong effect of installing excess capacities.

For a reduction of the variability of the solar power part of the electricity supply, CSP plants might be an option as they can be adjusted in a certain range due to their heat storage device. So in section 5.7 it has been investigated how a substitution of PV power by CSP effects the required energy storage capacity. The MEET model showed, that a rising ratio of CSP plants even increases the required energy storage capacity. A ratio of 50 % CSP and 50 % PV power increases the required energy storage capacity by already 37 % (fig.: 5.27). This is based on the facts that first, the CSP plants are only able to compensate variations in electricity demand and solar radiation by a range of seven full load hours and not of seasons. Second, CSP plants are only able to make use of the direct solar radiation while PV cells can use the diffuse component as well. This makes the CSP plants even more sensitive to the seasonal cycle, as clouds and thereby the diffuse part of solar radiation increase during winter time over Europe (compare fig.: 3.6 (a)). Nevertheless, as the efficiency of CSP power plants is about 2.6 times higher than of PV plants, the required power plant capacity follow a exponential decrease with a rising ratio of CSP (fig.: 5.27) which would be especially interesting when costs for energy storage capacities are low.

6.5.1. Energy storage and energy intensive industry

Coming to the energy storage itself, a lot of other options to those discussed in section 6.1 are possible. Large battery facilities, for example, could be a further alternative to pumped hydro power storage, CAES or hydrogen and methane storage plants. Batteries offer an energy density of one or two orders of magnitude higher than pumped hydro or CAES (Bünger et al., 2009) by having a comparable storage cycle efficiency to the as well high efficiency of pumped hydro power in the range of 80 % or even higher (Bünger et al., 2009).

Energy could even be stored in energy intensive goods such as aluminium instead of storage plants. In this case it is not possible to give the electricity back to the supply system, but having enlarged production capacities on could shift a part of the production process to periods of excess electricity. Especially high electricity intensive industries like the aluminium production show a high potential and the aluminium can be easily stored. Germany's aluminium industry has a potential of 12.6 TWh per year and the whole world has even 660 TWh per year (Bünger et al., 2009). Comparing this number with the total required energy storage capacities for all MEET model regions, the globally required energy storage capacity of about 532,TWh turns out to be even lower. But at the end, a flexible used energy intensive industry might help, but will never totally substitute the energy storage. Because, for example, Europe's industry in total uses about 40 % of the electricity (Bertoldi and Atanasiu, 2009). So even when this industry would totaly shut down it could not compensate a deficit larger than this demand of the industry. For about 2700 h a year, energy storage plants would have to supply more than this 40 % of power demand in a wind and PV power only supply scenario without excess capacities (fig.: 5.22). Therefor a flexibilised industry by installing higher production capacities could only reduce the load of required energy storage plants by approximately a halve.

The MEET model which has been developed for this thesis is a powerful tool to investigate the behavior of electricity supply scenarios on an one hour time resolution for the whole cycle of a year. After a detailed description of the MEET model, the focus of this thesis is the electricity supply by wind and PV power as the major electricity sources for scenarios of a future electricity supply based on renewable energies. Thus, general behaviour of using renewable power plants and the energy storage requirements were worked out in order to provide a base of options for a renewable electricity supply. In future, further effects of using additional technologies should be investigated by using the MEET model to learn more about the options to design electricity supply even more efficient. For example the use of load management in a smart grid, electric cars as part of the electricity system, bio power and hydro power, wave power to shift a part of the wind power load (Mayer (2010)) or even a remaining share of coal and gas power plants.

After working out all the influences of the different power plant and power management technologies on the electricity supply, it will be the economic market that bring out the future electricity supply. Of course, policy can take influence on it as well by arranging subsidies or taxes. The representation of renewable energies in economic models, such as GREET, RICE or the WEM, can be improved with the results of the MEET model. The MEET model is therefor an important step in developing future electricity supply strategies.

6.6. An estimate of an electricity supply of Europe by wind and PV power

Combining now the results shown before, the major points of an electricity supply system for Europe based on wind and PV power can be summarised in this section.

Starting with the highest energy storage investment cost of 150 EUR per kWh storage capacity assumed in tab.: 6.3 one can investigate the most critical scenario for a wind, PV and excess power capacity scenario for Europe. Eq.: [6.6] or fig.: 6.7 (e) developed in section 6.3 leads to electricity generation costs of 0.18 EUR/kWh for the mentioned storage investment. This electricity generation cost can be reached by using a power plant ratio of 30 % wind and 70 % PV power plant capacity and an excess capacity of 36 %.

Regarding the annual electricity demand of Europe with 3956 TWh/a, the total annual cost for the electricity supply sum up to about $712 \cdot 10^9$ EUR/a. This is double the European electricity expenditures in 2012 (Löschel, A. and Erdmann, G. and Staiß, F., 2012).

The required power plant capacity is in total 2994 GW (section 5.1.2 fig.: 5.2 (c)) without excess capacity. Considering the 36 % excess capacity the scenario ends at 4072 GW required power plant capacities. Regarding the 30 % wind and 740 % PV power ratio, 1222 GW wind and 2850 GW PV power plant capacity needs to be installed.

In section 3.13 wind power is given with an area demand of 80 m^2 per kW installed power and PV power with 7 m^2 per kW. The required land area of these power plants would be about 97760 km^2 for the wind power plants in Europe(about 0.96 % of the Europe land area) and about 19950 km^2 (about 0.2 % of the Europe land area) for the PV power in Europe. Both areas will be easily available as Bofinger et al. (2011) suggests a potential available area for the use of wind power in Germany with a fraction of 8 % and Braun and Oehsen (2012) suggests a fraction of 0.8 % for PV in Germany.

The total required energy storage for Europe is in total 72 TWh (eq.: [6.2] or fig.: 6.5) and would be feasible as well as Scandinavia has a potential of pumped hydro power storage plants of 121.5 TWh storage capacity (Sterner et al., 2010). Using a methane underground storage would require a storage of only $18.5 \cdot 10^9$ m^3 of which $175.5 \cdot 10^9$ m^3 were already installed in 1999 in Europe (Sedlacek, 1999).

7. Conclusion and outlook

The electricity supply sector requires about 38 % of the global primary energy demand and its energy demand is expected to further increase in future. This sector is reponsible for approximately 26 % of the total anthropogenic CO_2 emissions (Wheeler and Ummel, 2008). Due to anthropogenic climate change and limited resources of gas, oil, and coal, a change of the electricity supply system is needed emediatly. This thesis investigates the options for an electricity supply based on renewable energies. Therefore, an electricity supply model was developed and major dependencies for electricity supply, mainly based on the most promising sources (Heide et al., 2010), wind and PV power and energy storage capacities as an existential component were worked out.

7.1. Options for an electricity supply based on renewable energies

Electricity supply models covering almost all scales from regional to global and simulating a time range from one year up to 200 years have been developed to investigate options for a future electricity supply and to work out strategies to implement them (an overview is provided by tab.: 2.1).

Because technology prices, as for PV power plants, can change quite dramatically (Arvizu et al., 2011), it is challenging to predict price developments for future scenarios. Therefore, electricity models that base their decisions for an electricity supply system on minimise the costs, are highly dependant on the assumptions of technology prices. Other models focusing only on the simulation of wind and PV power are quite limited in their use.

To have the option to investigate the behaviour of different power plant combinations and getting time series for the annual electricity supply and energy storage requirements on an one-hour basis, the Meteorological based Energy Equilibrium Testing (MEET) model has been developed as part of this thesis. So, basic dependencies for the use of different power plants can be worked out considering a high temporal resolution to improve thereby assumptions in economic models that calculate for future electricity scenarios typically on an one year time interval.

The MEET model is set-up as a global electricity supply model subdivided into seven model regions, most on a continental scale. Customised regions can be defined as well by the user, if required. To calculate the volatile electricity generation by weather dependant renewable energies using power plants, global weather data for the years 2000 to 2010 are available for the MEET model. To define an electricity supply scenario, ten power plant types (nuclear, coal, gas, biomass, hydro power, CSP, PV, wave, onshore and offshore wind power plants) are represented in the MEET model. The electricity demand of the regions will be balanced by the defined power plant mix, while taking energy storage capacities into account. Further options such as power management, electric cars or adding of excess power plant capacities are implemented.

The use of power plants in the MEET model is evaluated against other models and the weather dependant power plants are evaluated in addition against existing power plants of their type. Compared to other models (Lanz et al., 2009; Teske et al., 2012; Nitsch et al., 2010a), the MEET model tends to have more full load hours of nuclear and coal power for electricity scenarios with a low share of renewable energies. The reason for the discrepancy between the models is that the MEET model is, in contrast to other models, not optimised for today's energy mix. Otherwise, the MEET model enables the investigation of future energy scenarios with higher shares of renewable energies in an independent way. For the direct comparison of modelled and existing weather dependant power plants, the annual electricity generation varies within 1 % to 22 %, depending on the power plant type. A major point for the difference is the model grid size of 2.5° with the highest influence for plant sites in areas with a strong gradient in the energy potential.

Finally, the MEET model might not calculate in all cases the power plant output very precise for every single site, the general behaviour of the power plants is well represented and that is what is required to investigate electricity supply scenarios. Therefore, the MEET model with all its represented power plants, adjustable power supply options, and multiple years of weather data is a powerful tool to work out fundamental behaviour of interaction of power plants, energy storage requirements and to identify tipping points in a conversion of the electricity supply system.

Solar radiation and wind are the renewable energies offering the highest potentials and thereby wind and PV power are supposed to become the main renewable energies in electricity generation (Heide et al., 2010). Due to their volatile availability an electricity supply system based on wind and PV power will require energy storage capacities to balance the weather dependant electricity generation and the man made demand. Because the seasonal availability of wind and solar radiation usually shows an anti-correlation, the ratio of wind and PV power can be chosen to minimize the required energy storage capacity. The behaviour of different ratios of installed wind and PV power plant capacities and the therefore required energy storage capacity varies considerably from region to region depending on their weather conditions.

On average the MEET model region of Europe with its annual electricity demand of 3956 TWh requires at least an energy storage capacity of 3.8 % of the annual electricity demand for a ratio of 30 % wind and 70 % PV power plant capacity. Going away from this optimal mix can increase the required energy storage capacity for Europe by a factor of up to 4.6. In contrast to that, model regions being part of the subtropical high pressure belt around 30° latitude tend to have a higher ratio of PV power like 90 % PV power for North America or even to 100 % PV power as Asia and Africa, because this regions offer quite constant solar radiation all over the year. But good wind conditions can counter this effect as for South America and Australia, where the lowest required energy storage capacity of 4.3 % and 4.9 % of the annual electricity demand appears for a 50 % wind and 50 % PV power ratio.

An efficient option to reduce the required energy storage capacity further, just by using wind and PV power, is to install excess capacity of these power plants. This additional electricity generation leads to an strong decrease of the required energy storage capacities. For the region of Europe, an excess capacity of already 10 % of the required power plants reduces ther required energy storage capacities by about a half and converges to an energy storage capacity of only 0.19 % of the annual electricity demand or 16.6 h of average power demand. This decrease can be found for all regions and beside the reduction of the required energy storage capacity, additional electricity is available that could be used.

The combination of the MEET model results for the varying wind and PV power ratios and the excess capacities lead to a map indicating the range of options for the basic electricity supply by wind and PV power and the related energy storage requirements based on this parameters. In some regions pumped hydro power as the only energy storage technology, can become challenging or even impossible to provide the required capacities except for high excess power scenarios. So energy storage capacity can be a limiting factor, but with technologies such as hydrogen or methane underground storage, almost all scenarios should be feasible.

Scandinavia is supposed to have a potential for pumped hydro storage of 121.5 TWh (Sterner et al., 2010) which is already in the right order of the required energy storage capacity of 150 TWh for Europe in the case of the 30 % wind and 70 % PV power scenario even without excess power plant capacities. To manage this storage capacity for Europe by underground gas storage about $125.2{\cdot}10^9$ m^3 of generated hydrogen or $37.6{\cdot}10^9$ m^3 methane have to be stored by the assumption of an efficiency of 0.39 for using the stored gas to generate electricity (Höflich et al., 2010). Already in 1999 Europe had underground gas storage capacities of $175.5{\cdot}10^9$ m^3 (Sedlacek, 1999) i.e. four times as much as required.

Due to the fact that pumped hydro power storage plants have a high efficiency and under ground gas storage offer a high storage capacity it is of interest to split the energy storage tasks with respect to periods of storing time. Götz (2013) found that a period of 24 h is a favorable storage circle time to separate short time storage (STS) and long time storage (LTS). Doing this separation, the MEET model results show that the STS capacity needs to be almost two orders of magnitude smaller than the LTS capacity for the 100 % renewable scenario. While the LTS is used for 2.9 full cycles per year of its storage capacity, the STS does 165.6 full cycles per year and thereby its annual energy volume is about the same as for the large LTS but saving losses due to its high efficiency.

Facing the required land area required by wind and PV power plants, even the 100 % wind power scenario of Europe requires only 1.87 % of the total area which is no problem as even for Germany with its high population density 8 % of the area are assumed to be valide for wind power (Bofinger et al., 2011). The 100 % PV power scenario requires only 0.3 % of the area of Europe while 0.8 % are assumed as realistic for Germany (Braun and Oehsen, 2012). Therefore all other ratios of wind and PV power will be feasable as well regarding the required area, especially considering the fact that the areas could be used for additional purpose as well like for farming in the case of wind power or housing in the case of PV power.

The influencing factor of the realisation of an energy supply system is not only the required energy storage capacity and the required area to install the power plants but the costs for this electricity shape the supply system. By using fit functions to describe the required energy storage capacity in dependency of the installed ratio of wind and PV power and the required power plant capacity and the decrease of energy storage capacity by excess power plant capacity, the resulting cost of electricity can be calculated. As cost for energy storage capacities can vary over a wide range depending on the geography and the storage technology, different cost scenarios from 1 EUR / kWh to 150 EUR / kWh storage capacity were investigated (Vardag, 2010). For the low energy storage costs excess power plant capacity is not of interest and the cheaper wind power plants are favoured resulting in electricity costs of just under 0.09 EUR / kWh. When storage capacity costs rise above 10 EUR / kWh the optimisation of wind and PV power becomes more interesting and for 150 EUR / kWh the 30 % wind and 70 % PV power scenario turns out as best with electricity costs of 0.47 EUR / kWh. Adding of excess power plant capacities become interesting at storage capacity prices exceeding 10 EUR / kWh. For 150 EUR / kWh of storage capacity, an excess power plant capacity of 36 % leads to a reduction of electricity costs down to 0.18 EUR / kWh. One has to remember that this costs are only the generation costs without additional taxes and costs for the electricity grid, but still they are feasable regarding today's cost for electricity generation in Germany of 0.085 EUR / kWh in 2013 (Lange, 2014), where environmental damages due to CO_2 and nuclear waste are not included.

A transition of today's electricity supply towards a 100 % renewable scenario requires knowledge at what share of wind and PV power additional electricity storage capacity will be needed and how fast this demand will rise. Therefore a transition for Europe has been simulated where a share between 50 % and 60 % of wind and PV power to the total power plant mix starts to exceed the already existing 2.5 TWh energy storage capacities of Europe (EURELECTRIC, 2011). Then the required capacity increases exponentially up to 150 TWh with a slight reduction coming close to the 100 % wind and PV power supply scenario and the utiliced capacity of coal and nuclear power plants declines fast.

Additional effects of different power plant types on the energy storage requirements have bin investigated as well, but the MEET model offers much more options for further investigations on specific electricity supply scenarios. Thereby the MEET model can be seen as a tool to evaluate supply strategies and to improve the representation of especially weather dependant renewable energies using power plants in economic models having a temporal low resolution for their calculations.

7.2. Further investigations and developments to be done

For this thesis, the MEET model has been developed and general dependencies of required energy storage capacities mainly on the use of wind and PV power has been investigated to form the base of designing electricity supply systems with a high share of renewable energies.

As a next step, much more scenarios could be investigated by using the MEET model to understand specific effects on an electricity supply system by using different power plant types or load management options.

A further improvement of the MEET model should be done in terms of implementing the explicit simulation of an electricity grid to improve the placement of power plants in the model areas and to work out where the major energy fluxes occur and which power line capacities might be required to take the advantage of, for example, an interconnected Europe.

Finally the challenges of climate change and limited resources are facing not just the electricity sector but the heat supply and mobility as well. One can make use of synergy effects as combined heat and power plants, electric heat pumps that might be used in times of excess electricity or electro mobility and even electro chemical generated hydrogen or methane as fuels for the mobility sector. Models considering all this sectors, as for example the WEM (International Energy Agency, 2011), improved by detailed analyses as done by the MEET model, will help to evaluate the options we have for a sustainable future.

A. Solar position

The position of the sun in the sky is defined by the solar angle α_s and the azimuth angle α_a. α_s is defined as the angle between the horizon and the sun and α_a as the angle on the horizontal plane starting with 0° in the North and going clockwise. To calculate those for each location on the earth at any time, the algorithm of DIN 5034 as described in Quaschning (2009) and Nunnenmann (2011) has been used for the MEET model. The position of the sun is mainly needed for the calculations of photovoltaic and solar thermal power presented in chap.: 3.7 and 3.8. In the following the main equations will be presented.

For the calculation, the day in the year, the absolute number of days in the year, the Coordinated Universal Time Coordinated (UTC) and the coordinates of the position in latitude ϕ and longitude λ are needed.

Starting with the variable J, which describes the part of the track the earth has followed on its way around the sun of the considered year in degrees.

$$J = 360^\circ \cdot \frac{\text{day of the year}}{\text{number of days in the year}} \qquad \text{[A.1]}$$

Now it is possible to determine the declination δ in degrees, which means the angle between the earth's equator and the sun. Due to the tilted rotation axis of the earth against the normal of the plain, in which the earth is going around the sun, the declination varies from -23.5 $^\circ$ to +23.5 $^\circ$ through the year.

$$\delta = (0.3948 - 23.2559 \cdot cos(J + 9.1^\circ) - 0.3915 \cdot cos(2 \cdot J + 5.4^\circ) - 0.1764 \cdot cos(3 \cdot J + 26^\circ)) \qquad \text{[A.2]}$$

The difference between the apparent solar time and the mean solar time can be described by the time equation (teq) as:

$$\begin{aligned} \text{teq} &= \frac{1h}{60} \cdot (0.066 + 7.3525 \cdot cos(J + 85.9^\circ) + 9.9359 \cdot cos(2 \cdot J + 108.9^\circ) \\ &+ 0.3387 \cdot cos(3 \cdot J + 105.2^\circ)). \end{aligned} \qquad \text{[A.3]}$$

It gives the difference between the effective time when the sun is at its zenith on a considered place and the over the year averaged time. So the apparent solar time (AST) can be calculated with the UTC scaled by a factor depending on the longitude λ of the position and the teq in the way:

$$\text{AST} = \text{UTC} + \frac{1h}{15^\circ} \cdot \lambda + \text{teq}. \qquad \text{[A.4]}$$

Finally the hour angle needs to be calculated by:

$$\omega = (12h - \text{AST}) \cdot 15^\circ/h. \qquad \text{[A.5]}$$

ω describes the angle between the noon position of the sun and the effective position in degree.

Considering the above presented equations [A.1] to [A.5], the solar angle α_s and the azimuth angle α_a can be calculated for each latitude ϕ and longitude λ coordinate on earth by equation [A.6] and [A.7].

$$\alpha_s = arcsin\left(cos\left(\omega\right) \cdot cos\left(\phi\right) \cdot cos\left(\delta\right) + sin\left(\phi\right) \cdot sin\left(\delta\right)\right) \qquad [A.6]$$

$$\alpha_a = \begin{cases} 180^\circ - arccos\left(\frac{sin(\alpha_s)\cdot sin(\phi) - sin(\delta)}{cos(\alpha_s)\cdot cos(\phi)}\right) & \text{for AST} \leq 12\,\text{h} \\ 180^\circ + arccos\left(\frac{sin(\alpha_s)\cdot sin(\phi) - sin(\delta)}{cos(\alpha_s)\cdot cos(\phi)}\right) & \text{for AST} > 12\,\text{h} \end{cases} \qquad [A.7]$$

B. Example of MEET model data in and output

The MEET model uses input files, allowing the user to specify energy supply scenarios to simulate with the MEET model. In this way, the settings can be easily adjusted without changing the source code of the MEET model. The MEET model requires many input data files described in section 3.19 such as wind, CSP and wave power plant specifications, the electricity demand of the model regions, weather data of each grid cell and time step, and especially the supply scenario settings given by the 'run_file.txt' (appendix B.1).

At the end of a simulation, the MEET model offers a variety of output, described in section 3.21, containing informations about power plant potentials, the positioning of the used power plants, hourly electricity generation for each power plant type, the required power plant and energy storage capacities (appendix B.2).

To provide an overview how this data are formated and how to use the 'run_file.txt' to create an electricity supply scenario, some examples are provided in this section based on an example scenario with a 60 % share of wind and PV power plants for the model region of Europe and an annual electricity demand of 3956 TWh (for the detailed settings see appendix B.1).

The content of data files presented in this section is written in *small cursive letters* while the explanations are in the standard text.

B.1. The 'run_file.txt' and 'electricity_demand.txt' to specify supply scenarios

To design an energy supply scenario to simulated with the MEET model, the user has to enter the annual electricity demand of the regions in a separated file (here 'electricity_demand.txt') and all the other specifications into the 'run_file.txt' file that is located in the main MEET model folder. In the following the content of this files will be presented and explained step by step.

Run File

——————————————————————-

In order to save computation time when simulating multiple scenarios with the same weather data, the MEET model is subdivided into two model parts that can run independent. Part I calculates the global potentials of renewable energies based on the weather data and Part II simulates the electricity supply scenarios for the model regions. Both model parts can be selected or unselected by entering '1' or '0'.

CHECK FOR RUN PART I AND/OR PART II OF MODELL [1=RUN, 0=RUN NOT]

——————————————–

model_data_part

0

model_energy_part

1

Beside the pre defined seven model regions, the MEET model enables the user to define an individual model region at any place on earth. To do so the 'area_switch' has to be '1'. If active, the position and size of the rectangular region can be defined by the coordinate of the left bottom corner and the number of grid cells of the region in east and north direction.

INDIVIDUAL OR FIXED MODEL AREAS [1=CREATE IT SELF, 0=USE STANDARD MODEL REGIONS]

——————————————–

area_switch

0

(POSITION AND SICE OF CHOOSEN AREA - discrete position of grid!)

left_bottom_lat

55.0

left_bottom_lon

7.5

lat_steps

1.0

lon_steps

1.0

*(lat_steps*lon_steps = number of points)*

For an easy use of the MEET model on different computers, the path to the MEET model folder, its sub folder for in and out put and input data files for the model regions and their electricity demand (described below the run_file example) can be insert below.

PATH OF CALCULATED ENERGYS FOLDER

——————————————–

calc_energy

C:\Uni-HD\MEET\ee-energy

PATH OF INPUT FOLDER

——————————————–

input_path

C:\Uni-HD\MEET\input_data

INPUT

———————————————————-

input_area

C:\Uni-HD\MEET\input_data\continentgrid_60.txt

input_area_coast

C:\Uni-HD\MEET\input_data\continents_coast_60.txt

input_demand_curve_el

C:\Uni-HD\MEET\input_data\electricity_demand.txt

The amount of model grid cells in east and north direction, the number of time steps, the duration of a time step in hours, the size of a model grid cell in degree longitude and latitude, and the number of model regions are defined below. Followed by the number of modelled years of weather data and a switch allowing a second method to read weather input data depending on their format (0 if meteorological date is without separator and 1 if after each time step the data is separated). Usually this numbers should not be changed as they are defined for the model region and weather input data. Only if new defined region data or weather data having an other spacial or temporal resolution are available, this part can be adjusted.

SICE OF DATA ARRAY

———————————————————-

iend

144

jend

73

tend

8753

time step

1

grid step

2.5

area num

7

model_years

1

data_timestep_separator_switch

0

The data file locations of wind, CSP and wave power plants can be adjust in the part below.

INPUT DATA: USED POWERCURVE OF WINDTURBINE

——————————————————-

windturb_powercurve

C:\Uni-HD\MEET\input_data\Powercurve_Nordex_N90.txt

windturb_powercurve_offshore

C:\Uni-HD\MEET\input_data\Powercurve_REpower_5M.txt

INPUT DATA: USED POWERMATRIX OF WAVEENERGYCONVERTER

——————————————————-

wave_powermatrix

C:\Uni-HD\MEET\input_data\Power-matrix_wavedragon.txt

INPUT DATA: USED CSP specifications

——————————————————-

parabolic_csp

C:\Uni-HD\MEET\input_data\Parabolic_CSP.txt

The following part is the most important to define an electricity supply scenario as here the mix of power plant capacities can be defined either in kW power or in per cent of the total required power. The power plant mix is given for all seven model regions in the order the regions are defined in tab.: 3.2. So the scenario for Europe is given by the mix defined at the third position of the power plant types (18 % onshore wind power, 0 % offsore wind power, 46 % PV power, 0 % wave power, 11 % hydro power, 0 % CSP, 1 % bio power, 8 % nuclear power, 9 % coal power, and 11 % gas power).

ENERGY-MIX SETTINGS OF REGIONS

——————————————————-

(0 use kW values; 1 use % values)

installed_power_switch

1

percentage_wind_power

0.0

10.0

18.0

0.0

50.0

10.0

50.0

percentage_wind_off_shore_power

0.0

0.0

0.0

0.0

0.0

0.0

0.0

percentage_solar_cells_power

100.0

90.0

42.0

100.0

50.0

90.0

50.0

percentage_wave_power

0.0

0.0

0.0

0.0

0.0

0.0

0.0

percentage_hydro_power

0.0

0.0

11.0

0.0

0.0

0.0

0.0

percentage_csp_power

0.0

0.0

0.0

0.0

0.0

0.0

0.0

percentage_bio_power

0.0

0.0

1.0

0.0

0.0

0.0

0.0

percentage_atom_power

0.0

0.0

8.0

0.0

0.0

0.0

0.0

percentage_coal_power

0.0

0.0

9.0

0.0

0.0

0.0

0.0

percentage_gas_power

0.0

0.0

11.0

0.0

0.0

0.0

0.0

The MEET model calculates the amount of power plant capacities required for an electricity supply by the power plant mix defined above. Now the user can define an excess capacity (over capacity) of power plants for each model region. If activated, the MEET model installs an additional per cent fraction of the minimum required power plants to the supply scenario (section 3.18).

EXCESS CAPACITY

———————————————————-

(0 for minimum needed power plants; 1 for percentage of installed overcapacity on the minimum capacity)

overcapacity_switch

0

overcapacity_percentage

0.0

0.0

0.0

0.0

0.0

0.0

0.0

As bio-fuels are a limited energy source, the maximum available energy per model region can be defined below.

POWERGENERATION LIMITS OF REGIONS in [kWh]

———————————————————-

max_biomas_el

405000000000

245000000000

137000000000

78000000000

239000000000

0

58000000000

The MEET model is able to calculate a load management to optimise the electricity demand for the electricity generation (section 3.15). Below the number of time steps, a load is allowed to be moved and the fraction of load that is movable in per cent can be defined.

LOAD MANAGEMENT

———————————————————-

(number of time steps)

range_of_load_move

0

factor_of_load_move

0.10

Electric cars, requiring additional electricity can be used for load management as well if considered in a supply scenario. Below the number of cars, the daily driven km, the battery capacity and the share of cars being in use at the same time are defined.

LOAD MANAGEMENT WITH ELECTRIC VEHICLES

————————————————————-

(on = 1; off = 0)

ev_discharge_switch

0

(per region)

number_of_ev

0

0

0

0

0

0

0

(per region [integer])

ev_km_per_day

50

50

50

50

50

50

50

(in kWh)

akku_capacity

40

(per region)

(bigger than 0.042 if once a day)

fraction_of_ev_in_use

0.1

0.1

0.1

0.1

0.1

0.1

0.1

Once a thermal power plant is switched of, it needs time to cool down before generating electricity again to avoid material damages. This time can be defined in hours below.

POWERPLANT BREAK MANAGEMENT

——————————————————-

(1 = minimum)

t_min_off_atom

55

t_min_off_coal

14

t_min_off_gas

3

The path to the folder where the MEET model output is stored is given as last point of the 'run_file.txt'.

PATH OF OUTPUT FOLDER

——————————————————-

output_path

C:\Uni-HD\MEET\output_data

The 'electricity_demand.txt' presented below starts with the annual electricity demand in GWh of the seven model regions (tab.: 3.2). Therefore region tree (Europe) requires 3956300.00 GWh / a. The sown demand has been taken from the Statistical Review of World Energy by BP (2009). Below the total demand of the individual regions, the sum of the electricity demand curve data is given, followed by the hourly values of the demand curve it self. In the standard case the demand curve is the demand of Germany in 2008 given by ENTSO-E (2014). This demand curve will be scaled by the MEET model to the demand of the simulated regions.

total_base_demand_el

Total base demand of model regions in GWh

9053100.00

5171700.00

3956300.00

638400.00

1049700.00

43700.00

272261.90

demand_sum

Sum of demand curve

495526580

demand_curve_el

start: 1.1.2008 0:00 hourly data in MW

48071

47488

45605

43701

42016

40879

39283

36278

⋮

Figure 3.3 (a) provides the characteristics of the demand data for the whole year.

B.2. Examples of MEET model output files

The most important output of the MEET model is summarised in a html file that will be presented in a web-browser after the simulation has been finished (see section 3.21 and fig.: 3.14 and 3.15) and in the .csv files called 'results_region#_energy.csv' while # denotes the model region number.

The 'results_region#_energy.csv' (described in section 3.21) contains the hourly values of the electricity generation of each power plant type, the electricity demand and the use of the energy storage and allows thereby most analysis of the modelled energy supply scenarios. As example the variable names and the first 24 h of data in kWh are presented below for an Europe scenario with 60 % wind and PV power share and weather data of 2009

el_sum_wind_hist	el_sum_atom_hist	el_sum_coal_hist	el_sum_gas_hist	el_demand_hist	el_storage_hist	el_storage_hist_power	el_import	el_sum_pv_hist	el_sum_wind_offshore_hist	el_sum_wave_hist	ev_loading_hist	ev_akku_state_hist	el_sum_hydro_power_hist	el_sum_bio_hist	el_sum_csp
0.324174E+08	0.115000E+09	0.111173E+09	0.284580E+08	0.348910E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.474777E+08	0.143841E+08	0.000000E+00
0.357935E+08	0.115000E+09	0.943336E+08	0.284580E+08	0.335457E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.474879E+08	0.143841E+08	0.000000E+00
0.388513E+08	0.115000E+09	0.821877E+08	0.284580E+08	0.326379E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.474981E+08	0.143841E+08	0.000000E+00
0.410986E+08	0.115000E+09	0.671877E+08	0.284580E+08	0.313637E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.475083E+08	0.143841E+08	0.000000E+00
0.438571E+08	0.105117E+09	0.503100E+08	0.284580E+08	0.289645E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.475186E+08	0.143841E+08	0.000000E+00
0.441485E+08	0.105486E+09	0.503100E+08	0.284580E+08	0.290315E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.475288E+08	0.143841E+08	0.000000E+00
0.415840E+08	0.108797E+09	0.503100E+08	0.284580E+08	0.292423E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.135060E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.475390E+08	0.143841E+08	0.000000E+00
0.428134E+08	0.115000E+09	0.532147E+08	0.284580E+08	0.308080E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.666043E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.475492E+08	0.143841E+08	0.000000E+00
0.419685E+08	0.115000E+09	0.663171E+08	0.284580E+08	0.328950E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.152630E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.475594E+08	0.143841E+08	0.000000E+00
0.395956E+08	0.115000E+09	0.647702E+08	0.284580E+08	0.352878E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.431008E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.475696E+08	0.143841E+08	0.000000E+00
0.372680E+08	0.110297E+09	0.503100E+08	0.284580E+08	0.365269E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.769726E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.475798E+08	0.143841E+08	0.000000E+00
0.315024E+08	0.737715E+08	0.503100E+08	0.284580E+08	0.362275E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.116259E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.475900E+08	0.143841E+08	0.000000E+00
0.258935E+08	0.575000E+08	0.503100E+08	0.280296E+08	0.363385E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.139671E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476003E+08	0.143807E+08	0.000000E+00
0.243738E+08	0.694260E+08	0.503100E+08	0.280296E+08	0.366571E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.132437E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476105E+08	0.143841E+08	0.000000E+00
0.229194E+08	0.111044E+09	0.503100E+08	0.280296E+08	0.388878E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.114571E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476207E+08	0.143841E+08	0.000000E+00
0.238422E+08	0.115000E+09	0.111367E+09	0.284580E+08	0.420806E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.801238E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476309E+08	0.143841E+08	0.000000E+00
0.251481E+08	0.115000E+09	0.129000E+09	0.611266E+08	0.428918E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.366183E+08	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476411E+08	0.143841E+08	0.000000E+00
0.262656E+08	0.115000E+09	0.129000E+09	0.850907E+08	0.423721E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.632881E+07	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476513E+08	0.143841E+08	0.000000E+00
0.284904E+08	0.115000E+09	0.129000E+09	0.742703E+08	0.408806E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476615E+08	0.143841E+08	0.000000E+00
0.309872E+08	0.115000E+09	0.129000E+09	0.669889E+08	0.404032E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476718E+08	0.143841E+08	0.000000E+00
0.299550E+08	0.115000E+09	0.129000E+09	0.745099E+08	0.410531E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476820E+08	0.143841E+08	0.000000E+00
0.330349E+08	0.115000E+09	0.129000E+09	0.492002E+08	0.388311E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.476922E+08	0.143841E+08	0.000000E+00
0.330482E+08	0.115000E+09	0.129000E+09	0.286657E+08	0.367800E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.477024E+08	0.143841E+08	0.000000E+00
0.310527E+08	0.115000E+09	0.113764E+09	0.284580E+08	0.350371E+09	0.515976E+09	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.477126E+08	0.143841E+08	0.000000E+00
...															

The MEET model calculates for each weather dependent power plant (onshore and offshore wind power, PV power, CSP, and wave power) the theoretically generated electricity for each model grid cell and each hour of the modelled period. This time series of electricity generation potentials based on the weather data given to the MEET model are saved in data files in the 'ee-data' folder. An example for the PV power is presented below. The data header indicates the unit of the calculated data, followed by the grid cell size in degree latitude and longitude, the number of grid cells in east and north direction, the number of provided time steps and the time step size in hours. After the header, the matrix with the dimension lon-steps times lat-steps times t-steps is written, containing the electricity generation data of the power plant type.

*solarpower in kWh for 1m**2 module per gridpoint*

gridstep	*2.50*
lon-steps	*144*
lat-steps	*73*
t-steps	*8753*
timestep	*1*

0.0000000	*0.0000000*	*0.0000000*	...
5.32825701E-02	*5.32880388E-02*	*5.32934964E-02*	...
5.32769561E-02	*5.32821119E-02*	*5.32872714E-02*	...
5.39858863E-02	*5.39910384E-02*	*5.39962053E-02*	...
5.68328388E-02	*5.68379648E-02*	*5.68430871E-02*	...

$\ddots$

C. List of Abbreviations

Abbreviations	Definition
AST	Apparent Solar Time
BRL	Model of Boland, Ridley and Lauret for diffuse solar radiation
CCS	Carbon Capture and Storage
CDO	Climate Data Operators
CHP	Combined Heat and Power
COP	Conference of the Parties
CSP	Concentrating Solar Power
DICE	Dynamic Integrated Climate-Economy
DIN	German industry for standards (Deutsches Institut für Normung)
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DWD	German meteorological service (Deutscher Wetterdienst)
EEG	German law on renewable energies (Erneuerbare-Energien-Gesetz)
ENTSO-E	European Network of Transmission System Operators for Electricity
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GIS	Geographical Information System
GREET	Global Resource Extraction and Energy Transformation
HCE	Heidelberg Center for the Environment
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inner Tropical Convergence Zone
IWES	Institut für Windenergie und Energiesystemtechnik
LTS	Long Time Storage > 24 h
MEET	Meteorological based Energy Equilibrium Testing
MERRA	Modern-Era Retrospective analysis for Research and Applications
NCEP	National Center for Environmental Prediction

Abbreviations	Definition
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaic
REMix	Renewable Energy Mix for sustainable electricity supply
RICE	Regional Integrated Climate-Economy
SEXPOT	Spatiotemporally-Explicit Power and Transmission
SimEE	Simulation of the feed in of renewable energy
	(Simulation der einspeisung Erneuerbarer Energien)
STS	Short Time Storage $\leq 24\,\mathrm{h}$
UTC	Universal Time Coordinated
WEM	World Energy Model
WEPROG	Weather & Wind Energy Prognosis
ZEW	Zentrum für Europäische Wirtschaftsforschung

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