The effect of storage and interconnection on the optimal mix of intermittent renewables in Europe

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December 2014 - June 2015

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Abstract

Due to their intermittent nature, wind and solar power are difficult to integrate in the European electricity system. In this thesis the potential benefits for grid integration of choosing an optimal mix and distribution of wind and solar power were studied. The effect of interconnection on the capacity credit and curtailment of intermittent renewables was studied for a scenario for 2050 developed by Greenpeace. The effects of interconnection and storage on the optimal distribution of wind and solar capacity were studied as well. The study was based on high resolution reanalysis weather data and a method to generate wind and solar production profiles based on reanalysis weather data was demonstrated.

The optimal mix of wind and solar power in a copper plate Europe consists of 74% wind energy and 26% solar energy for a combined total of 78% intermittent renewables in total annual production. Without interconnection, the share of wind decreases and the share of solar energy increases, indicating that interconnection favors wind power which is reflected in the lower cross-border correlations in wind power, particularly between countries on different latitudes. Increasing volumes of high power storage favors solar power, until the ratio in production from intermittent renewables is then 60% wind to 40% solar. Storage increases the capacity credit of renewables in an optimal distribution of capacity only when there is interconnection. As long as there is enough interconnection, choosing an optimal mix of intermittent renewables makes them easier to integrate on the grid, improves their capacity credit and reduces curtailment of their output.

Contents

Glossary

Annual demand: Demand for electricity per year in TWh.
Capacity credit: Load carrying capability of a unit of capacity. Can be expressed as a percentage of nameplate capacity of the unit or as the reduction of the backup required in the system.
Capacity factor: Ratio between power output of a unit and its nameplate capacity at a given moment in time.
Curtailment: Reduction in the output of wind and solar power due to excess of power.
Demand: Demand for electricity (or load) in GW.
Intermittent renewables: Wind and solar. Refers to power or energy (GW or TWh) depending on context.
I-RES: Intermittent renewables
Penetration: Share of a technology in annual electricity production.
Remainder: The difference between I-RES power production and demand (in GW). Can be positive or negative.
Solar: Photovoltaics (PV) and concentrated solar power (CSP).

Introduction

Background

Renewable electricity generation technologies harvesting wind and solar energy have become widespread in Europe over the past decade, particularly since the European targets for renewables for 2020 were put in place in 2009 (European Commision, 2014). Renewable electricity is seen as a way to reduce carbon emissions in the electricity system and decarbonizing the electricity system is an important step in reducing overall carbon emission. Currently, the production of intermittent renewable electricity still accounts for a limited percentage of total annual electricity supply (European Commision, 2013). The member states of the European Union have all formulated goals for 2020 in which share of renewable electricity will increase to over 20 percent. Most of the newly installed renewable capacity will be wind and solar. In the long term the share of intermittent renewables (I-RES) will continue to increase (European Commision, 2011) to further reduce carbon output of the electricity sector.

Intermittent renewables cannot be dispatched and their output is difficult to predict. When the share of renewable electricity becomes high, typically over 20% (Hammons, 2008), it poses a problem for the stability of the grid. The renewable production must be balanced by the conventional plants which have to adjust their production. There will be less room for base load plants and more thermal capacity will need become demand following. The exact penetration level where intermittent renewables destabilize the grid depends on the flexibility of rest of the installed capacity and the interconnection with neighboring grids (Poyry, 2013).

There are multiple options to balance supply and demand with high shares of intermittent renewables. The four main ones are: demand response, storage, interconnection and optimization of the geographical distribution of intermittent renewables over Europe. These solutions are interrelated, particularly interconnection and the distribution of capacity over Europe depend on each other to be effective. Although the weather in most European countries is highly correlated (Poyry, 2013), neither wind speeds nor solar irradiation are fully correlated, let alone the combination of the two. Therefore, there is potential to balance intermittent electricity production through grid integration and by optimizing the distribution of I-RES capacity over Europe. It should be noted that grid integration has an economic benefit whenever there are large price differences between regions and not just in the case of high penetrations of intermittent renewables.

Previous research

The potential for storage, interconnection and choosing a smart geographic distribution of I-RES to accommodate high shares of I-RES on the grid has been the subject academic research.

Studies on the impact of interconnection on the European grid are often focused on wind power. The integration of wind power can be difficult because wind power is intermittent and not always predictable. For the integration of high shares of wind energy on the grid, flexibility is required from the rest of the system and with limited flexibility, the penetration level of wind can go up to just 20-25% (Lund, 2005). Interconnection can increase this penetration level.

In the TradeWind study (European Wind Energy Association, 2009) the effect of interconnection on wind in the European system was studied. They found that interconnection greatly improves the case for wind power and that the capacity credit of wind depends on interconnection, going up to 12% per unit of nameplate capacity. The capacity credit of renewables is the amount of thermal capacity that a unit of renewable capacity can reliably replace. France, the UK and Ireland were critical points in the system where more interconnection is required.

These studies were focused on wind, but the combination of wind and solar in Europe with a high penetration of intermittent renewables has been studied as well. Interconnection benefits wind power more than solar power (Schaber & Steinke, Parametric study of variable renewable energy integration in Europe, 2012). With interconnection, the optimal ratio of wind to solar in I-RES production is 75% wind to 25% solar and without interconnection this goes to 55% wind and 45% solar. Without interconnection, more energy needs to be curtailed and the match between production and demand is poor. Beyond 80% I-RES penetration, curtailment and the mismatch between production and demand increases rapidly. In this study storage was not considered.

The ability of storage to match demand profiles with production profiles for PV and wind power has been studied in the article 'Electricity storage for intermittent renewable sources' (Rugolo & Aziz, 2012). They found that both the solar and the wind profile could be matched with demand profiles, when the storage has a capacity/power ratio of 10-40 to 1, meaning that storage technologies such as batteries, compressed air energy storage and some pumped hydro could deal with intermittence on these timescales. This study did not take grid expansion into account.

The integration of high shares of intermittent renewables will require grid expansion as well as storage, so integrated studies which consider both options are needed. The question how much of each is required has been explored in the study 'Grid vs. storage in a 100% renewable Europe' (Steinke, Wolfrum, & Hoffman, 2013). Main conclusions are that even in a 100% renewable Europe backup capacity is still needed. The amount depends on the degree of interconnection, from a reduction of required backup capacity of 40% for a well-interconnected Europe to 20% for a poorly interconnected Europe. Storage and interconnection are complementary: more storage capacity means less interconnection is required and vice versa.

The studies mentioned in the previous paragraphs focused on the effects of interconnection and storage for a given distribution. A different approach is to take the installed wind and solar capacities in Europe as variables and to optimize the mix and distribution of these I-RES capacities. An example of this approach is the article 'Seasonal optimal mix of wind and solar power in a future, highly renewable Europe' (Heide, 2010). This study aimed to find the optimal mix of wind and solar power in Europe that minimizes the need for seasonal storage. They found that the share of wind in the optimal mix is higher than the share of solar power because wind is better matched to the seasonal demand profile than solar power. If the share of intermittent renewables is decreased, production from fossil sources replaces solar power. At 80% I-RES penetration level, the seasonal optimal ratio of wind to solar energy is 55% to 45%.

To summarize; a number of studies has been done on the effects of intermittent renewables on the European electricity system, both for wind energy and for the combination of wind and solar energy. Often either interconnection or storage is considered, few studies compare these directly. The timescale that is studied is either diurnal or seasonal and little comparison between the two is made. The potential benefits of choosing the right distribution of wind and solar capacity over Europe are understudied especially in relation with storage and interconnection.

This means there is a need for a study on the optimal distribution of I-RES over Europe including the effect of interconnection and storage on the optimal mix. Such a study should be based on a large set of real historic weather data and not just on production data because it is a more fundamental approach to assess the long term potential for intermittent renewables.

This need should be fulfilled, since in many studies the distribution of capacity is exogenous and the focus is on storage and interconnection, but choosing the right distribution of capacity can boost the value of interconnection and storage for I-RES integration. Optimizing the distribution of I-RES capacity is not yet always seen as a way to enable the integration of I-RES on the grid.

This leads to the following research question:

- What is the effect of interconnection and storage on the optimal mix and geographical distribution of I-RES capacity over Europe with high penetration levels of intermittent renewables and how does the distribution of capacity affect curtailment and the need for backup power?

With the following sub questions:

1. What is the effect of interconnection on the capacity credit and curtailment of I-RES in Europe?
2. What is the effect of I-RES on the variability in the remainder and what are the patterns in I-RES production on diurnal and seasonal timescales?
3. What is the optimal distribution of I-RES capacity to match I-RES production with the demand profile?
4. What is the effect of interconnection on the optimal distribution of I-RES capacity and the resulting need for curtailment and backup capacity?
5. How does storage affect the optimal mix of wind and solar power in a system with a high share of I-RES?

To answer these questions, a model to calculate production of wind and solar energy based on installed wind and solar capacities in Europe is needed. A model with a combination of production profiles derived from real weather data and installed capacities of wind and solar per country can be used to create profiles of the electricity production by intermittent renewables. Two ways to distribute the capacity will be studied. The first is to distribute capacity over a country in the same way as it is distributed now and the installed capacities per country are taken from a scenario developed by Greenpeace. The second is to optimize the installed capacities per country such that I-RES production follows the demand profile as much as possible.

Scope and resolution

The study is focused on systems with high penetration of intermittent renewables at around 50% of annual demand or higher. Europe won't have such high shares of intermittent renewables in the following decades, so the target year is set to 2050. This means that assumptions for technology are not based on current installed capacity but on state of the art technology. Some intermittent renewable technologies which may play a role in the future are not explicitly included in this thesis, such as ocean or tidal energy.

The spatial scope is Europe, excluding the Balkan countries, Moldavia, Belarus, Russia and the Ukraine.

The available weather data limits the spatial and temporal resolution. Detailed weather data is often not publicly available. The data set used in this thesis is the Watch Forcing Data methodology applied to ERA-Interim weather data (WFDEI) by EU WATCH. This dataset includes all relevant parameters (insolation, temperature, wind speeds) on a 0.5 by 0.5 degree grid. Time resolution is 3 hours. The dataset covers land and the coast, there is no coverage of regions that are far offshore (EU WATCH, 2015).

Scenario

In order to create distributions of capacity of wind and solar for the model a scenario is selected from a number of scenarios developed by other parties. The development of electricity demand and the share of wind and solar in the capacity mix of each European country in 2050 is highly uncertain. Scenarios can be used to explore the future of intermittent renewables in Europe. The scenario that is selected should be seen as a possible outcome in the future and not as a prediction. No probability is assigned to the selected scenario. The scenario is a starting point for the optimization and the effect of interconnection and storage on key indicators can by studied for the scenario.

Scenarios that can be used in this study must feature both projections for the annual electricity demand per country, as well as the capacities wind and solar energy per country. Not all scenarios for the future of the European electricity system provide all of these variables. The selected scenario should also feature a high share of intermittent renewables, because the integration of intermittent renewables gets more difficult with higher penetration levels.

Multiple scenarios for 2050 were considered. The following three scenarios stood out as potential candidates:

- The 'X10 – Big and market' scenario developed by ENTSO-E in their comprehensive e-Highway 2050 study (ENTSO-E, 2014) was as a scenario with a low share of renewables, at 60 percent.
- The 'Roadmap 2050' study by the European Climate Foundation includes many detailed scenarios for 2050 (European Climate Foundation, 2010). Their 80% renewables scenario was considered for this study.
- The Greenpeace 'Renewables 24/7' scenario is a scenario with a very high share of renewables (98%) including a high share of intermittent renewables at 50% of annual demand (Greenpeace, EREC, 2010). It is also well-documented scenario, featuring installed wind and solar capacities per country and a grid study based on this scenario has been published. (Energynautics GmbH, 2011). This grid study can be used as a reference to compare the results with.

Because of the high share of renewables and good documentation of the scenario in the Energynautics grid study the Greenpeace scenario was selected. This scenario is explained in detail in the following section.

Greenpeace Energy [R]evolution: 2050

The scenario selected to review in this study is the 'Advanced Energy [R]evolution' scenario developed by Greenpeace and Energynautics GmbH (Greenpeace International, 2010). This scenario is a global scenario for energy for the year 2050. Part of this scenario is the predicted development of the electricity system in Europe. Energynautics performed a grid study based on this scenario applied to the European electricity market (Energynautics GmbH, 2011). This study has predictions for the capacities of all generation types on a per-country basis. An overview of the production per generation type for this scenario is given in the following table.

EU-27	TWh/yr	%
Total Generation	4202	100
Total Renewables	4110	97.8
Wind (onshore+offshore)	1392	33.1
PV	622	25.4
CSP	446	10.6
Hydro	391	9.3
Biomass	554	13.2
Other Renewables	705	16.8
Curtailed energy	294	7.0

Table 1: Production per generation type in the Energy [R]evolution scenario by Greenpeace in 2050. Results of grid study by Energynautics GmbH.

Key assumptions for this scenario are a highly interconnected Europe, very strong political support for renewables and rapid price decreases by technological learning for solar PV and wind power. Development of the full potential for hydroelectric energy in Europe is assumed as well as support for the use of biomass in electricity generation. Demand response to shave off peaks in demand when I-RES production is low and large efficiency gains at end-use are also assumed in this scenario.

The scenario has a high share of renewables at 97.8% of annual electricity demand and around 50% of annual demand is covered by intermittent renewables. The increase in annual demand compared to 2012 is approximately 25%. The scenario features CSP, PV, wind power and some tidal energy, the last of which was not modeled in this this thesis. The high share of renewables and the inclusion of CSP, PV and wind power based on an interconnected Europe make this scenario a suitable starting point.

A few key parameters for the scenario were unspecified in the Energynautics grid study, namely the ratio of offshore wind to onshore wind for each country and the development of annual demand on a country level. The increase of the annual demand for each country was based on the increase of the peak demand for each country compared with 2012.

The ratio of offshore wind to onshore wind was based on the 2012 Energy [R]evolution scenario (Greenpeace International, 2012), because this scenario did specify a ratio of onshore to offshore wind capacity in Europe of 60% to 40%.

Offshore wind capacity was divided over countries based on their potential for offshore wind. Countries on the North Sea are considered to have the highest potential for offshore wind, with a maximum offshore wind capacity of 55% of the total wind capacity. Baltic countries and countries on the Mediterranean were assigned a maximum share of offshore wind capacity of 33%.

With these constraints the wind capacity was divided over all countries such that the total offshore wind capacity is 40% of total installed wind capacity. The installed capacities of each technology per country is given in the following table:

COUNTRY	CSP (GW)	Wind on (GW)	PV (GW)	Wind off (GW)
Europe	99.1	305.0	544.0	200.1
Austria	0.0	6.8	11.0	0.0
Belgium	0.0	4.3	7.3	3.6
Bulgaria	0.0	3.4	13.4	0.0
Switzerland	0.0	0.8	16.5	0.0
Czech	0.0	2.4	8.5	0.0
Germany	0.0	44.9	61.0	43.9
Denmark	0.0	6.3	5.6	5.3
Estonia	0.0	1.5	3.2	0.6
Spain	57.1	46.4	48.8	20.2
Finland	0.0	5.1	3.7	0.0
France	5.0	36.7	79.3	34.7
UK	0.0	39.6	37.2	37.8
Greece	7.8	6.5	24.4	2.5
Hungary	0.0	1.4	12.2	0.0
Ireland	0.0	4.3	5.0	3.6
Italy	15.6	21.0	61.0	8.4
Lithuania	0.0	1.3	3.7	0.5
Luxembourg	0.0	0.3	2.4	0.0
Norway	0.0	4.3	10.2	3.6
Latvia	0.0	0.9	3.7	0.3
Netherlands	0.0	6.1	12.2	5.1
Poland	0.0	28.6	36.6	26.1
Portugal	13.7	10.3	24.4	4.0
Romania	0.0	5.2	13.4	0.0
Slovakia	0.0	0.5	7.2	0.0
Sweden	0.0	15.9	8.5	0.0

Table 2: Installed capacities in Europe in the Advanced Energy Revolution scenario developed by Greenpeace and Energynautics GmbH.

Methods

To optimize the installed capacities of I-RES in Europe and to analyze the Greenpeace scenario time series of wind and solar production and time series of electricity demand are needed. These are combined in a model to optimize the installed capacities per country and calculate key indicators.

In order to be able to calculate I-RES production for multiple scenarios capacity factor profiles for per country for onshore wind, offshore wind, PV and CSP are needed. To generate these profiles historic weather data with a high spatial resolution of 0.5° by 0.5° is used. This divides Europe in grid cells of +-40 by 40 kilometers.

The methods are divided in three sections:

- First each grid cell is weighted according to their potential for wind or solar power and this is combined with high resolution weather data to create capacity factor profiles.
- Second, the capacity factor profiles are aggregated to country level and used to analyze the Greenpeace scenario.
- Third, the installed capacities per country are used as variables in the optimization with the objective to match I-RES production with the electricity demand profile, based on the capacity factor profiles per country.

The capacity factor profiles tell us at each time step how much power is produced as a fraction of the rated power in a grid cell. When this is combined with installed wind and solar capacities in a country, production profiles can be generated and these can be analyzed.

The installed capacities per country from the Greenpeace scenario and the optimized installed capacities are combined with capacity factor profiles and key parameters such as the capacity credit of I-RES, the amount of stored, exchanged and curtailed energy and the variability of the remainder are extracted. An overview is given in the following figure:

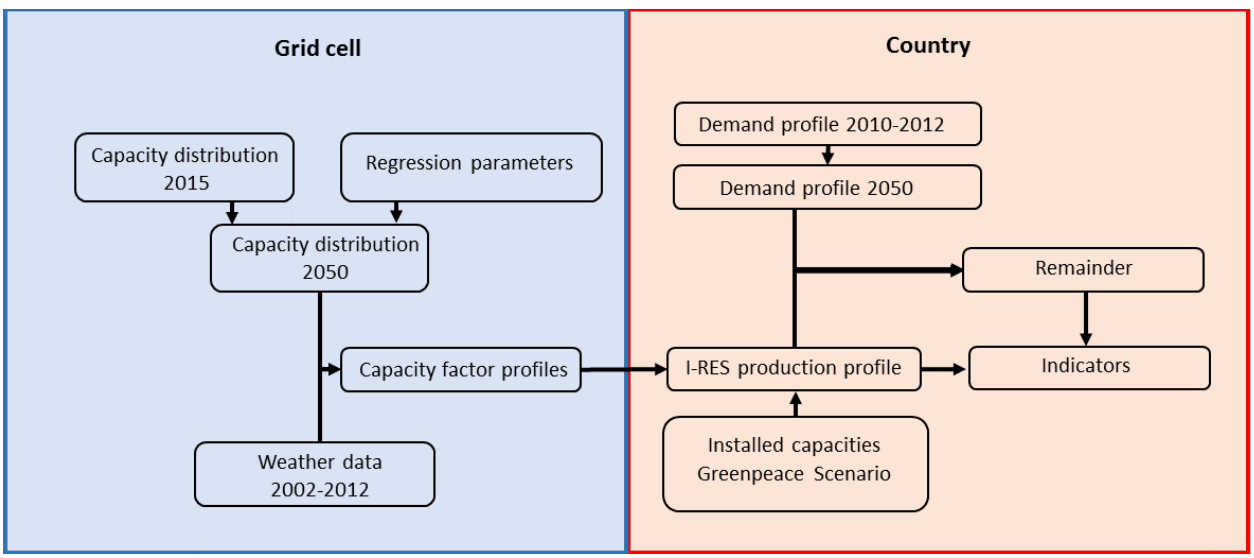

Figure 1: Schematic overview of the process. All data in the left part of the image is on a grid cell level (40x40km) and the data on the right has been aggregated to country level. First the current capacity distribution is combined with regression and a capacity distribution for 2050 is given. This is combined with weather data to generate capacity factor profiles. Then on country level, the installed capacities in the Greenpeace scenario are combined with these profiles to calculate I-RES production per country. Using the demand profiles for 2050 and the I-RES production profiles, the remainder and key indicators are calculated.

Nonlinear constrained and unconstrained optimization is used to optimize the installed capacities in Europe. The variables in the optimization are the installed capacities of wind and solar in each country. The objective function is the absolute value of the sum of the net remainder, which measures the mismatch of the I-RES production and the demand profile. The goal of the optimization is to reduce this mismatch between I-RES production and demand. The remainder is defined as follows:

$$R(t) = D(t) - P(t)$$

Where $R(t)$ is the remainder in GW, $D(t)$ the demand in GW and $P(t)$ is the power production from intermittent renewables in GW. The net remainder $Rn(t)$ is calculated after taking storage into account. This is explained in the optimization section.

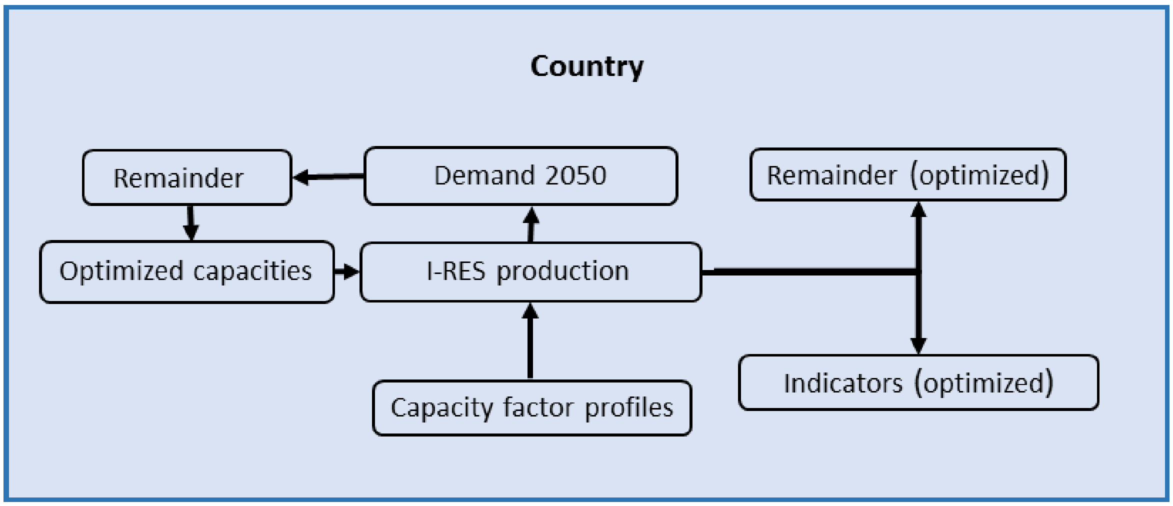

Figure 2: Schematic overview of the optimization. The spatial resolution is always on country level. The capacity factor profiles are used to calculate I-RES production, which is compared with the demand profile to calculate the remainder. The net remainder is minimized by changing the installed capacities. This leads to a new I-RES production profile and a new iteration can start. When the optimization has converged, the net remainder and other key indicators are calculated using the optimized capacity distribution.

In the following section the methods behind the creation of the profiles and the optimization are explained, starting with the capacity factor profiles.

Regression

The capacity distribution within a country used for the country level capacity factor profiles is generated using the current distribution of capacity as an example for 2050. Regression analysis is used on the current distribution of capacity to determine the relation between installed capacity and the input parameters so that each grid cell can be assigned a weight. Linear regression is a technique to fit a linear function with multiple independent parameters through a set of observations. These parameters are wind resources, population density, roughness and elevation for wind. For solar PV the parameters are insolation and population density. Data on installed wind capacity was taken from the TU Delft Enipedia database (TU Delft, 2015), data on installed PV capacity from the European Photovoltaics industry association (EPIA , 2013). The regression was performed using the same geo-data that was used later to assign weights to each grid cell.

Each grid cell in a country gets a weight according to the number of grid cells in a country. This weight is modified by a function that linearly depends on the value of the parameters in that grid cell. Finally, the weights are normalized so that the sum of the weights is equal to 1. The capacity in each grid cell is then the weight times the total capacity in a country for the scenario.

Capacity factor profiles

The grid cells within countries are weighted to generate more accurate capacity factor profiles by combining the weights with weather data in a model. The logical structure of the model used to create the production profiles is a three dimensional structure of cells, a matrix. This matrix consists of two dimensional structures; grids. Each grid consists of rows and columns which represent longitude and latitude of the grid cells. The grid cells are 0.5° by 0.5° in size. Each grid represents a new variable, for instance a country identifier, annual insolation or population density and so on. Time series are simply a large stack of grids, each grid representing a time step.

The variables and time series are divided in four main groups:

1. Constants
2. Capacity distribution
3. Weather data
4. Grid cell-level capacity factor profiles

Constants

This group consists of grids which are needed in the rest of the entire model; to find the country to which each cell belongs, extract coordinates and align the stack of grids. It also features the parameters used in the regression to distribute the capacity of wind and solar energy. This data was extracted from their sources using ArcGIS and imported into MatLab.

1-4: Master grid/x and y coordinates/country

These grids feature basic information needed in the model. The master grid determines whether a grid cell is onshore or offshore and is used to align all other grids, the x and y coordinate grids give the longitude and latitude for each grid cell and the country grid gives each cell an identifier which is assigned to a European country.

5: Land use

This grid is based on the European Corine land cover classes database (European Environment Agency, 2015). It is a grid which defines the type of land use in each grid cell; agriculture, forest, industrial, urban etcetera. The original data has a much higher spatial resolution than the rest of model. The value of each grid cell was determined by the majority of the high-resolution data within that grid cell.

6: Surface roughness

The surface roughness parameter is a measure for the typical scale of objects which affect the wind speeds near the surface. The surface roughness parameter is a parameter which determines the relation between wind speed and altitude which is needed because wind speeds are given at 10 meters height while windmills have hub heights of over 100 meters.

The surface roughness depends on the type of land use. The relation between the Corine land cover class and the roughness parameter was taken from 'Roughness length classification of Corine land cover classes' (Silva, Ribeiro, & Guedes, 2009) which is based on the European Wind Atlas published in 1989 and the KNMI HYDRA project.

7: Land area

This is the area of land in each grid cell. The land area depends on the longitude and latitude of the cell and on the size of water bodies within a grid cell. The land area has been taken from NASA's socioeconomic data and applications center. (NASA SEDAC, 2015)

8: Population density

The population density has been retrieved from the same source as the land area so that the data matches. Population density is for the year 2010. (NASA SEDAC, 2015)

9: Elevation

The elevation layer is a single grid with the average elevation within the grid cell. The elevation is a proxy for how mountainous a grid cell is. Data was taken from the EU water and global change project. This is also the source for the weather data. (EU WATCH, 2015)

10: Annual wind resources

The annual wind resources per grid cell are based on the 3 hourly weather data at 10 meters. It is calculated by setting the wind speed values above a threshold value of 30 m/s to zero. This threshold value represents a typical cut out speed of a turbine. The cubes of the wind speed in each grid cell are then added to obtain the annual wind resources in that grid cell. This is because the energy density in a flow of air scales with the velocity squared and the amount of air scales with the velocity (Twidell & Weir, 2005). The mean of the annual wind for 2011 and 2012 has been used to determine the wind resources. (EU WATCH, 2015)

11: Annual insolation

This grid is calculated by integrating the 3 hourly insolation data over the years 2011 and 2012 and taking the average. The data used is the global horizontal irradiation (GHI) in watts per square meter. (EU WATCH, 2015)

Weather data

The weather data used comes from the ERA-interim reanalysis project which combines data used in forecasting the weather and aligns this data so that it forms a consistent dataset for the period 1979 to 2012. The dataset used is the Watch Forcing Data for Era-Interim (WFDEI) dataset, where the ERA-interim reanalysis data set was used for the WATCH project. Data is available on a 0.5 degree resolution grid in 3-hourly intervals. They are time series of 2920 or 2928 grids per year (EU WATCH, 2015).

12: Temperature: 2002-2012

Temperature data was needed for the wind profiles because temperature affects the air density which influences output. Temperature data was expanded to offshore grid cells using nearest neighbors. (EU WATCH, 2015)

13: Wind speed: 2002-2012

The available wind speed data is the instantaneous wind speed in m/s at 10 meters in 3 hourly intervals. Wind speed between those measurements is unknown and there could be variations which affect the wind power production such as short periods of strong winds. Wind data was expanded to offshore grid cells by using the values of the nearest neighbors. (EU WATCH, 2015)

14: Insolation: 2002-2012

Data on the shortwave downward radiation or global horizontal irradiation (GHI) was available. This shortwave downward radiation is the input for all further calculations for PV production. DNI, direct normal irradiation was calculated based on this insolation data. The data is the mean over the previous 3 hours, in W/m^2

Capacity distribution weights

These grids are the weighing factors to distribute wind and solar capacity over countries on a high resolution. When combined with weather data this gives us capacity factor profiles. Wind onshore and wind offshore are treated separately. Solar PV and CSP are treated separately as well. These technologies have very different characteristics since CSP only works with direct irradiation.

For each technology in every country, the weights are normalized so they add up to 1.

15: Wind distribution onshore

For onshore wind the parameters used in the regression are:

1. Annual wind resources. These are measured by taking the cube of the 3 hourly wind speed data and summing these. When the wind speed is higher than the cut off speed for a wind turbine it is discarded by setting it to zero.
2. Elevation. At higher altitudes the air density is lower and wind turbines are more difficult to connect, affecting the installed capacity.
3. Population density. Wind mills often face local public opposition and suffer from the NIMBY-effect. This decreases the amount of wind capacity in densely populated grid cells.
4. Surface roughness parameter. Wind data is available at 10m altitude but wind turbine hub height is in the order of 100 meters. The amount by which wind speeds increase with altitude depends on the surface roughness. A rough surface with many terrain features decreases the wind capacity installed.

The current distribution of onshore wind capacity was taken from the TU Delft Enipedia database (TU Delft, 2015). The capacity distributions of France, Germany, Denmark, the United Kingdom, the Netherlands and Spain were taken as input data for the regression analysis. The geographical data that was used for the creation of the future capacity distributions was taken as input data for the regression.

The weight factor is then calculated from the regression coefficients as follows:

$$W_f = c_{pd} * Pd + c_{Rl} * Rl + c_e * E + c_w * W$$

Where W_f is the weight factor, Pd the population density in inhabitants/km^2, Rl the roughness length in meters, E the elevation in meters, W the annual wind resource in m^3/s^2 and c_x the regression coefficient of parameter x, in the inverse units of parameter x so the weight factor is dimensionless.

16: Wind distribution offshore

The offshore wind grid is a separate grid. Offshore grid cells were allocated to a country based on proximity. As the weather data was limited to the first 50 km offshore, offshore cells without weather data were filled with the weather data from adjacent cells. This creates uncertainty and the offshore wind speed is likely underestimated. The lack of offshore wind data limits the analysis to the first 100 kilometers off the coast.

Because the number of offshore wind farms is small it is difficult to perform regression. Increased distances to the shore and higher sea depths make offshore wind expensive and these factors are correlated. By distributing wind power over the grid cells that are close to the shore both of these effects are taken into account. Capacity is distributed according to the wind resources in each grid cell, using the regression coefficient for wind resources for onshore wind.

Data on the current location of offshore wind farms was taken from the 4C offshore online database (4C offshore, 2015).

17: Solar PV distribution

Solar PV can be installed on rooftops or in large ground mounted farms. Rooftop solar PV can consist of small systems in a residential area or larger systems on rooftops of commercial or industrial buildings. The segmentation of the PV market varies strongly between the different European countries (EPIA , 2013). The spread in market segmentation and the uncertainty in the development of the market segmentation make it difficult to spread capacity according to the type; ground mounted or rooftop. The diffuseness of installed PV capacity also makes it difficult to obtain accurate data on the capacity distribution. Data was taken from the Global Market Outlook for Photovoltaics 2014-2019 by the European Photovoltaic Industry Association (EPIA). Data is on provincial level and the quantity given is the capacity per capita, which is why the results need to be multiplied with the population density to obtain the capacity per area.

For the regression the following input parameters were used:

1. Annual global horizontal irradiation. The amount of annual radiation naturally has a strong influence on production and therefore on the capacity distribution.
2. Population density.

The weight factor is then calculated from the regression coefficients as follows:

$$W_f = (c_{pd} * Pd + c_{Rl} * Rl) * Pd$$

Where W_f is the weight factor, Pd the population density in inhabitants/km^2 and c_x the regression coefficient of parameter x, in the inverse units of parameter x so the weight factor is dimensionless.

18: Solar CSP distribution
Solar CSP uses mirror systems to concentrate direct solar irradiation. This radiation is absorbed by a working fluid which can transfer the heat to water for use in a conventional thermal cycle. The working fluid, often a molten salt, has a high heat capacity. The thermal mass of the system creates a lag between irradiation and power output. This makes solar CSP less subject to sharp peaks in power output than solar PV. The thermal mass of the system makes storing energy for a short amount of time possible. Unlike PV Solar CSP systems are necessarily large centralized units because a Rankine cycle is used to convert heat into electricity.

The distribution of solar CSP was not based on regression because the sample size is still very small. Instead, for each country the grid cells with irradiation in the highest third of a country were selected. Solar CSP capacity was distributed evenly across these grid cells. CSP is only installed in countries with high direct normal irradiation: France, Spain, Portugal, Greece and Italy.

Capacity factor profiles
These are the capacity factor profiles on a grid cell level. These are later aggregated to country level by weighing each grid cell with the weight factors calculated in the previous section.

19: Solar PV production
The production of PV is calculated based on data on global horizontal irradiation (GHI). This is the sum of direct (beam) and diffuse (sky) components of the solar radiation that reaches the surface in W/m^2. Solar panels are placed at an angle and in order to calculate the irradiation at an angle the irradiation from both separate components is usually required. This data is not available to us.

The alternative method that was used is based on the article 'Prediction of global irradiance on inclined surfaces from horizontal global irradiance' (Olmo, Vida, Foyo, Castro, & Alados, 1999). In this article, a relation was found between extra-terrestrial horizontal irradiation, global horizontal irradiation at the surface and irradiation on an inclined plane (Gψ).

Key parameter is the factor k_t which is the ratio between GHI and global extra-terrestrial irradiance (GEI). All atmospheric effects such as cloud cover, dust, humidity and atmospheric path length are contained within this parameter. The relation between global horizontal irradiance and global irradiance on an inclined surface (Gψ) is then as follows:

$$G\psi = \mathrm{GHI} * \mathrm{e}^{-\mathrm{k}(\psi^2 - \psi\mathrm{h}^2)}$$

Where k is the ratio between horizontal and extraterrestrial radiation$\frac{GHI}{GEI}$, ψ is the angle between the normal to the plane of the PV panel and the sun and ψh is the angle between the horizontal and the sun. Angles are in radians. Gψ and GHI are in W/m^2.

This relation is not fundamentally derived from theory but Olmo et al. have shown that it holds very well, particularly in situation with high insolation. The error is larger at shallow angles and in cases where the cloud cover is high. However, in those cases the production from PV panels is low so the final impact is reduced.

For the global extra-terrestrial radiation GEI there is the following equation:

$$GEI = G_0 * \cos\psi\mathrm{h}$$

Where G_0 is the solar constant at 1367W/m^2, with GEI in W/m^2

The angles ψ and ψh can be calculated in the following way (Twidell & Weir, 2005). Assuming that the PV panels are placed at the ideal angle which is the latitude:

$$\cos\psi = \cos\omega * \cos\delta$$

$$\cos\psi h = \sin\varphi * \sin\delta + \cos\varphi * \cos\omega * \cos\delta$$

Where ω is the hour angle, δ is the declination and φ is the latitude. All angles are in radians.

The hour angle (in degrees) is calculated as follows:

$$\omega = 15 * (t_{solar} - 12)$$

Where t_{solar} is the local solar time in hours.

The declination (in degrees) is calculated using the following formula.

$$\delta = \delta_0 * sin\left[\frac{360 * (284 + n)}{365}\right]$$

Where δ_0 is equal to 23.45° and n is the day of the year.

Using this method the global irradiance on the plane of the PV panels ($G\psi$) can be calculated. The capacity factor is then calculated as follows:

$$CF = \frac{G\psi(\mathrm{t})}{G_{stc}(t)}$$

With the irradiations in W/m^2. Because the capacity is defined as the power output at standard testing conditions the power depends on the rated power and the insolation compared with the insolation under standard testing conditions. This factor is DC and needs to be converted to AC with an inverter. A DC-AC efficiency of 95% is assumed.

Not all PV panels are placed in the optimal direction. This error is assumed to be symmetric which means that the misalignment of the solar panels has the same effect in the morning as in the evening and in the summer as during winter. This factor is set to 0.85. (van Sark, 2014)

The data available is the mean insolation over the past 3 hours. This means that the data is not instantaneous while the demand and wind data are instantaneous. To offset this the solar production data is shifted by 1.5 hours.

20: Solar CSP production

For CSP the Direct Normal Irradiation (DNI) is needed, which is the beam component of the solar radiation that reaches the surface. The ratio of global horizontal irradiance to global extra-terrestrial radiation (GHI/GEI) was taken as the value for the ratio between DNI and GHI. This is an approximation but clear skies with a high share of direct irradiation correspond to a high ratio of irradiation at the surface to extra-terrestrial irradiation.

CSP systems were assumed to have a Solar Multiple (SM) of 1. This means that the plant has a capacity factor of 1 under standard conditions. Standard conditions were set to 800 W/m^2 DNI in all of Southern Europe (Trieb, 2009). If DNI is higher than the standard conditions, the solar field feeds more energy into the system than can be converted. The excess energy is stored, with a maximum storage of 3 hours. This is based on the NREL CSP system advisor model (NREL, 2008).

21: Wind production

Wind production is calculated in two steps. First the wind speed data which is measured at 10 m altitude needs to be converted to the wind speed at the hub height. Then a wind speed-power profile is used to calculate the capacity factor at that wind speed.

The measured wind data is instantaneous. If there is a period of strong winds between measurements the calculated production is too low. However, because there are many data points per country periods of strong winds that are not measured in one cell may be observed in adjacent cells and the error averages out.

To convert the wind speed at 10 meters to the wind speed at the hub height the log wind profile was used:

$$v_h = v_{10} * \frac{\ln h}{\ln z} \bigg/ \frac{\ln 10}{\ln z}$$

Where v_h is the wind speed at the hub height h in m/s, v_{10} is the wind speed at 10 meters altitude in m/s and z is the roughness length in meters. Two hub heights were used for onshore and offshore (110 and 120 meters in 2050, respectively).

To relate wind speed at hub height with power output a wind speed-power curve is needed. Separate curves were made for onshore and offshore wind turbines. A selection of large modern wind turbines was used to model the power curves for 2050. Some of the capacity installed in 2030 may consist of wind turbines available today, but in 2050 the wind speed power curve may be different as the installed capacity will not consist of turbines available on the market currently and this creates uncertainty.

The wind turbines used for the onshore power curve are the following: Siemens 3.6MW 107m, Gamesa G128 4.5MW, General Electric 3.6MW 111m, Enercon E-126 7.5MW, Repower 126m 5MW. The wind speed-power relation was taken from the power curve database available through the UK Department of Energy and Climate Change. (UK DECC, 2015)

The wind turbines used for the offshore power curve are the following: Gamesa G128 4.5MW, Senvion 6.2MW 152, Siemens 6MW, Vestas 7MW offshore. The wind speed-power relation was taken from the power curve database. (UK DECC, 2015)

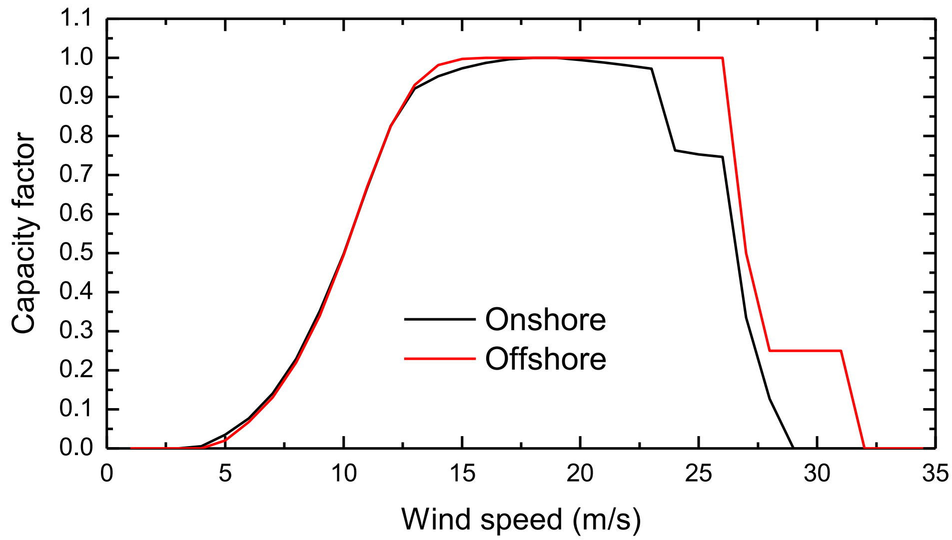

Figure 3: Resulting wind speed-power profiles based on a mix of large modern (2010-2015) wind turbines. Offshore wind has a slightly higher cut out speed than onshore wind. Steps at the tail of the function are caused by different cut out speeds among the turbines.

The capacity factor CF is then:

$$CF(v_h(t))$$

For offshore wind a small correction was made by increasing this capacity factor by 10% to a maximum of 1. This was based on the observation that minimum wind speeds are higher offshore than onshore. (Hsu, 1981).

Finally, a correction was made to incorporate the effects of temperature and elevation. Both these factors influence the air density so a modification factor was used on the capacity factor; a linear relation was assumed:

$$m = (1 - 0.1 * e) * (1 - 0.00347 * (T - 293))$$

Where m is the dimensionless modification factor, e the elevation in kilometers and T the temperature in degrees Celsius.

The wind speed-power curves are based on 20° Celsius at sea level. The correction for temperature and elevation yielded values between 0.93 (Spain in summer) and 1.04 (Denmark during winter).

Optimization and indicators

The capacity factor profiles for wind, PV and CSP are combined with the weight factors in order to create capacity factor profiles per country. Multiplying with the installed capacities per country this results in production profiles. These renewable production profiles are combined with demand profiles and a curtailment and storage module is added. This is the basis from which the indicators are calculated and the basis for the optimization.

The optimization takes the Greenpeace scenario as a starting point. The mismatch between production from renewables and demand is minimized in the optimization. The indicators of the Greenpeace scenario are compared for a copper-plate Europe and a European system without interconnection. Likewise, the optimizations are carried out for a copper-plate Europe and a European system without interconnection.

The goal of the optimization is to generate a capacity distribution which matches demand with production from I-RES as much as possible. This means the remainder is minimized, which is a time series of the difference between I-RES production and electricity demand.

$$R(t) = D(t) - P(t)$$

Where $R(t)$ is the gross remainder, $D(t)$ demand and $P(t)$ is the power production from I-RES, all in GW. When there is an excess of I-RES the remainder is negative, when there is a shortage the remainder is positive. The sign of this gross remainder determines whether energy can be stored, curtailed or whether there can be production from storage.

The optimization is based on either 3-hourly profiles or seasonal profiles. For the optimization based on 3-hourly profiles (3-h optimization) weather years 2010-2012 and demand profiles of 2010-2012 were used. For the seasonal optimization weather years 2002-2012 were used.

Demand

The annual electricity demand in the model was based on the annual demand by 2050 given in the Energynautics grid study based on the Greenpeace scenario. The demand profiles were based on data for 2010 to 2012 taken from the ENTSO-E database (ENTSO-E, 2015).

The increase of annual demand compared with the annual demand in 2012 was not distributed evenly across Europe. The relative change in annual demand for each country was not given in the grid study. Therefore the change in gross annual demand was based on the change in peak demand, which was given in the Energynautics grid study. Afterwards the demand profiles were scaled such that the total annual demand matches the Greenpeace scenario.

$$\forall c: D_{2050,c}(t) = \frac{P_{2050,c}}{P_{2012,c}} * D_{2012,c}(t)$$

$$\forall c: Dn_{2050,c}(t) = D_{2050,c}(t) * \frac{T_{2050,GP}}{\sum_{c,t} D_{2050,c}(t)}$$

Where $D_{2050,c}$ is the demand curve in 2050 of a country. $P_{2050,c}$ the peak demand of a country in 2050, $P_{2012,c}$ the peak demand of a country in 2012 and $D_{2012,c}$ the demand curve of a country in 2012, all in GW. $T_{2050,GP}$ is the total annual demand of all countries in 2050 in the Greenpeace scenario, in TWh. $Dn_{2050,c}(t)$ are the profiles normalized so that the total annual demand of all countries matches that in the Greenpeace scenario.

This simple extrapolation means that the yearly or daily pattern is not changed. New technologies such as electric vehicles, demand response and heat pumps could alter the demand profile in each country. Because of the high uncertainty in the development of these technologies and because demand response and electric vehicles can potentially act as storage these are not included in the fixed demand profile.

Storage and curtailment

The model includes a storage module. The storage is filled when there is an excess of I-RES. If the storage is full while there is an excess of I-RES, the excess energy is curtailed. If there is energy stored and there is a positive gross remainder the storage is emptied.

In the copper plate model there is a single storage volume. If there is no interconnection the total storage is divided over each country, with the volume per country based on annual demand in each country.

The storage module changes the remainder. The absolute value of the remainder decreases because less energy is curtailed and production from storage counts as production from I-RES. The remainder after storage is taken into account is called the net remainder.

The storage volume operates as follows:

$$
\begin{gathered}
if\ R(t) \leq 0\ and\ if\ S(t) < Sc \\
then\ R(t) = -R(t) \\
and\ S(t+1) = \min\big(Sc, S(t) + R(t)\big) \\
and\ Rn(t) = \mathrm{R(t)} - (S(t+1) - S(t)) \\
else\ if\ R(t) \leq 0\ and\ if\ S(t) \geq Sc \\
then\ Rn(t) = R(t) \\
else\ if\ R(t) \geq 0\ and\ if\ S(t) > 0 \\
S(t+1) = \max\big(0, \mathrm{S(t)} - \mathrm{R(t)}\big) \\
Rn(t) = R(t) + (S(t+1) - S(t))
\end{gathered}
$$

Where $S(t)$ is the stored energy in time step t and Sc is the storage capacity. $\mathrm{R(t)}$ is the gross remainder at time t and $Rn(t)$ the net remainder. All units are in GW, with a 3 hour time step a storage capacity of 200 GW is equivalent to 0.3 TWh. This storage volume can charge and discharge within 3 hours without any further constraints on the power. This is why it is referred to as high power storage.

Objective function

The production profile after taking the effect of storage into account should be matched with the demand profile. This is done by minimizing the following objective function:

$$\sum_{t=0}^{e} |(Rn_t)| = F_r$$

Where F_r is the objective function in TWh and Rn_t the net remainder at time t in GW. The absolute value of the net remainder has to be minimized. An example is given in the following figure.

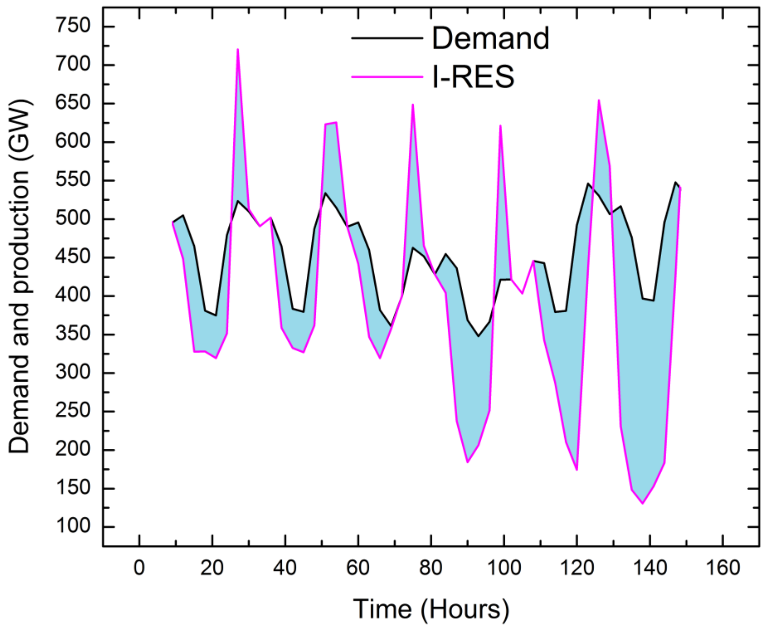

Figure 4: Example to illustrate the objective function. The mismatch between I-RES supply after taking storage into account and electricity demand needs to be minimized. This mismatch is the net remainder, which can be positive or negative. The absolute value of this net remainder, which is the blue area between the curves, is minimized in the optimization. Example is from the 3-h optimized capacity distribution, using weather data of May 2012 and the demand of 2012 extrapolated to match the demand in 2050 in the Greenpeace scenario.

The variables to be optimized are the capacities of wind onshore, wind offshore, solar PV and CSP in each country. This means that in the model with 27 countries there are 108 variables, although for many countries the upper bound on offshore wind and CSP capacity is zero.

	Wind onshore	Wind offshore	PV	CSP
Ireland	X_{11}	X_{12}	X_{13}	X_{14}
U.K.	X_{21}	X_{22}	X_{23}	X_{24}
Belgium	X_{31}	X_{32}	X_{33}	X_{34}
……….	$X_{..1}$	$X_{..2}$	$X_{..3}$	$X_{..4}$
……….	$X_{..1}$	$X_{..2}$	$X_{..3}$	$X_{..4}$
Greece	X_{261}	X_{262}	X_{263}	X_{264}

Table 3: Example to illustrate the variables that are optimized. The installed capacity of each technology in each country is a variable. With 26 countries this gives us 108 variables. Capacities are in GW.

The gross remainder depends linearly on each variable. However, the net remainder after storage and curtailment is optimized. The storage and curtailment functions can change $Rn(t)$ nonlinearly because the storage module contains multiple if statements, min and max functions. The absolute value of the net remainder the objective function is even more nonlinear. The presence of min, max and abs functions in the objective function makes the objective function and its derivatives discontinuous.

Optimization technique

The optimization is performed in MatLab using the global optimization toolbox. The fmincon function in MatLab is suited for constrained and unconstrained nonlinear optimization. The solving algorithm used in the optimization is the interior point algorithm. This algorithm has the advantages that it is fast and does not have large memory requirements, but it may be less accurate than other algorithms because it tends to iterate away from inequality constraint boundaries. The algorithm uses gradients and second partial derivatives.

Constraints

Each variable has lower and upper bounds. For all I-RES capacities $C_{t,n}$ where t is the technology and n the country the following applies:

$$0 \leq C_{t,n} \leq Cmax_{t,n}$$

With the capacities in GW. The maximum capacities depend on the optimization. For the unconstrained 3-hour and seasonal optimizations the maximum capacity per technology per country was set to 4 times the value in the Greenpeace scenario. These values correspond to a maximum of 0.5 MW/km^2 of onshore wind and 1 MW/km^2 of PV maximum. This is four times the wind power density currently installed in Denmark (Danish Wind Energy Association, 2015). For PV this maximum means that about 0.8% of the total surface is covered, assuming an efficiency of PV systems of 12.5%. These values are very high, but in line with theoretical maxima obtained in studied on the global potential for wind and solar energy (Ecofys, 2015) & (Moriarty & Honnery, 2012). For the constrained optimization the maximum value was set to 3 times the value in the Greenpeace scenario.

In the constrained optimization the total solar and wind capacity need to be the same as in the Greenpeace scenario:

$$\sum_{\forall w,n} C_{w,n} = \sum_{\forall w,n} GP_{w,n}$$

$$\sum_{\forall s,n} C_{s,n} = \sum_{\forall s,n} GP_{s,n}$$

Where $C_{w,n}$is the wind capacity installed in a country, $C_{s,n}$ the solar capacity installed in a country and GP stands for the Greenpeace scenario. Capacities are in GW.

Interconnection

The model uses either a copper plate or no interconnection at all. A copper plate means that demand, storage and production from intermittent renewables is summed as if the interconnection capacity is infinite. With no interconnection, countries cannot exchange any power. These are extremes but comparing the optimized distributions with and without interconnection gives an indication of the effects of interconnection.

Indicators

The following key parameters are calculated to compare the optimized distributions with the Greenpeace scenario and to compare the copper plate system with the system without interconnection.

I-RES penetration

I-RES penetration is the total net production from wind and solar power after storage and curtailment have been taken into account as a percentage of annual demand. Storage and interconnection will decrease curtailment and increase net production from I-RES.

Forced exchange

The forced exchange is the energy that has to be exchanged between countries in the system. Naturally, this parameter is only calculated for the interconnected system. If there is a country with a positive gross remainder where the total system has a negative gross remainder the positive gross remainders are the exchange at that time step. If countries have negative gross remainders while the sum of the remainders is positive, the absolute value of these negative gross remainders are the exchange at that time step.

Renewable capacity credit

The capacity credit is a measure of the dependability of a unit of capacity in a system. It is often defined as the effective load carrying capability of a unit and is often expressed as a percentage of nameplate capacity. If a unit has a capacity credit equal to 1 this means that the system can rely on the full capacity of that unit when the demand is high. If a unit has a low capacity credit this means that more other units are needed in the system to back these units up.

While some consider PV to be an energy only source of power with no capacity credit due to its intermittence, the peak following properties of PV during the gives it a capacity value (Perez et al., 2009). For wind power it has been shown that for small penetrations the capacity credit is almost equal to 1, but as the penetration increases, the capacity credit drops (Giebel, 2007). Furthermore, there are many measures of capacity credit. Some focus on the number of events where load is lost, others also take the duration and the amount of load into account (Milligan & Porter, 2008).

Whereas normally the capacity credit is defined as described before for a unit of either wind or solar capacity, the combination of wind and solar power is studied in this thesis. Therefore the definition of capacity credit used is the amount of backup capacity that can be replaced by the total capacity of wind and solar in the system. This is expressed as a percentage of peak demand. It is calculated in the following way:

$$Cc = \frac{Max\big(D(t)\big) - Max\big(Rn(t)\big)}{Max(D(t))}$$

Where Cc is the dimensionless capacity credit, $Max\big(D(t)\big)$ the maximum demand and $Max\big(Rn(t)\big)$ the maximum net remainder, both in GW. The maximum net remainder represents the moment in the time series where production from intermittent renewables is lowest compared with demand. The capacity credit is defined by these worst moments.

The capacity credit was calculated based on a time series of 5 years. In the case of no interconnection each country has its own capacity credit, the average is given in the results section.

The peak demand in Europe in 2050 is 671 GW, based on the profiles for 2010, 2011 and 2012. This is the maximum demand on which the capacity credit is based.

Total remainder

The sum of the absolute value of the net remainder is the objective function in the optimization. It is also calculated for the Greenpeace scenario.

Curtailed energy

Whenever the net remainder is negative when storage is full, power needs to be curtailed. The gross curtailment has to be allocated to wind and solar power. Curtailment is allocated to wind and solar production based on the share of wind and solar power in production at the time of curtailment.

Stored energy

The stored energy measures how well the storage capacity is utilized. To prevent double counting only the charged energy is counted.

Wind/solar production ratio

The ratio of wind to solar power in production after correcting for curtailment.

Results

In this chapter the results of the regression, correlations between I-RES production profiles, analysis of the Greenpeace scenario and the results of the optimization are presented in the following order:

- First the regression and the high-detail capacity distributions from the Greenpeace scenario based on the regression are presented.
- Second, correlations in normalized production profiles of wind and solar power between countries are studied based on the production profiles produced in our model.
- Third, the production profiles, storage and curtailment are studied for the Greenpeace scenario. The following key parameters are compared between a copper plate Europe and Europe without interconnection:

1: Share of intermittent renewables	5: Wind/solar capacity ratio
2: Exchanged energy	6: Wind/solar production ratio
3: I-RES capacity credit	7: Curtailed energy
4: Total net remainder	8: Stored energy

Table 4: Overview of key indicators for each capacity distribution. These are compared between copper plate Europe and Europe with no interconnection.

- Then the capacity distributions are optimized. First the optimization is based on the 3-hourly profiles, then on the seasonal demand and production profiles. A fully interconnected Europe and a European system without interconnection are compared using the key parameters in table 4. However, the optimization leads to different installed capacities for an interconnected Europe versus a European system without interconnection which makes it difficult to compare these directly. The following table gives an overview of the optimizations that were done:

Optimizations	Constraint: Total capacity per I-RES technology	Timescale	Interconnection
1	None	Seasonal	Copper plate & None
2	None	3-hourly	Copper plate & None
3	Same as Greenpeace	Seasonal	Copper plate

Table 5: Overview of the optimizations that were carried out. The first two have no constraint on total capacity, the final optimization has the constraint that the wind and solar capacities must be the same as in the Greenpeace scenario.

- Finally, the effect of storage on the optimal mix of wind and solar was studied by optimizing the installed capacities with different storage volumes. This was done for a copper-plate Europe on a 3-hourly timescale.

Capacity distribution

These are the results of the regression; to illustrate the relations between the installed capacities and regression parameters the capacity distributions based on the Greenpeace scenario are also presented in this section.

Solar

For solar PV, regression was based on province-level data. This gives us a limited number of data points. The output is capacity per capita. The next table shows that areas with a high population density have a lower installed capacity per capita and installed capacity is related to insolation. Both relations are statistically significant.

Capacity	W/inhabitant	Coefficient	Significance (P-value)
Population density	inhabitants/km^2	-0.83	0.01
Insolation	kWh/m^2	0.65	0.00

Table 6: Regression parameters, coefficients and p-values for the distribution of solar PV, based on data from the EPIA (EPIA, 2014). *P-values higher than 0.05 mean that the relation found is not significant.*

This is reflected in the R^2. The value of 0.96 is high, but it is not certain whether the correlations found on provincial level also apply on a 50 by 50 kilometer scale.

Multiple R	0.98
R Square	0.96
Observations	13

Table 7: R squared and number of observations of the regression for the distribution of onshore wind power based on data from the EPIA (EPIA, 2014).

The results from this regression were used to distribute the capacities in the Greenpeace scenario over the European countries. Capacity per country is given in the scenario, but the distribution within each country is based on the regression analysis. The results can be seen in the following figure:

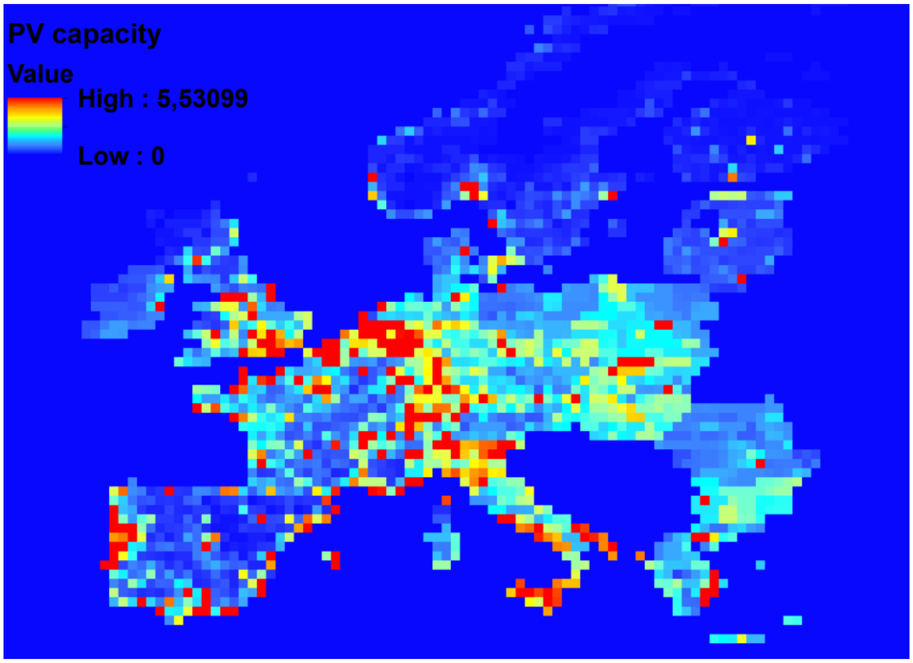

Figure 5: Distribution of solar PV capacity in 2050 in the Greenpeace scenario, based on regression. The parameters determining the distribution are population density and insolation. Red indicates high installed capacity, blue zero capacity. Capacity is in GW.

Population density has the most effect on the distribution of capacity, despite the lower capacity per capita for densely populated areas. For countries where PV on residential, commercial and industrial property dominates, this is realistic. However, the market segmentation differs strongly from one country to another. For instance, in France almost half of all PV capacity is ground mounted, whereas in Denmark virtually all PV is installed on residential rooftops (EPIA, 2014). In any case, this is an improvement over the simple assumption that PV is distributed evenly across countries and will improve the capacity factor profiles.

CSP capacity allocation to grid cells was not based on regression. Capacity was distributed evenly over the grid cells with the highest annual insolation in a country (70th percentile or above). This is because CSP plants are large facilities not bound to rooftops as PV often is. They can be placed wherever they yield the most.

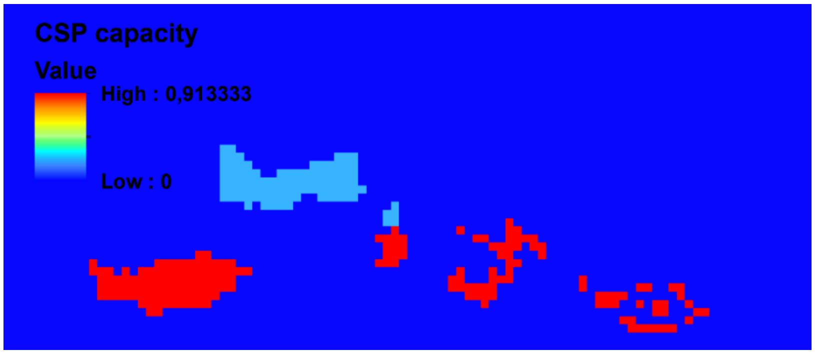

Figure 6: Distribution of CSP capacity in 2050 in the Greenpeace scenario, based on the grid cells with the highest insolation in each country. Red indicates high installed capacity, blue zero installed capacity. The outlines of Spain, Portugal, France, Italy and Greece can be recognized. Capacity is in GW

Wind

For onshore wind the regression was based on data on installed wind power from the TU Delft Enipedia. As expected, wind power, elevation and population density affect the installed capacity the most. The relation between the roughness parameter and the installed capacity is not significant. This is probably because the roughness parameter is determined for a 40 by 40 kilometer grid cell and wind power siting depends on the roughness parameter on a much finer resolution. Most likely the roughness parameter of wind power sites is overestimated and this will affect the production profiles.

Capacity	GW/km^2	Coefficient	Significance (P-value)
Population	inhabitants/km^2	-8.2E-04	0.02
Roughness	meters	-0.19	0.36
Elevation	meters	-1.9E-04	5.6E-01
Wind	v^3 summed	4.5E-06	1.2E-32

Table 8: Regression parameters, coefficients and p-values for the distribution of onshore wind, based on data from the TU Delft Enipedia. P-values higher than 0.05 mean that the relation found is not significant.

The R^2 value of 0.34 is low and it means that the capacity per grid cell is not fully explained by these four input variables alone. This is understandable as the data has a course spatial resolution, there may be nonlinear relations between wind power and these input variables, the roughness parameter is a poor measure of local conditions and there may be other variables unaccounted for.

Multiple R	0.58
R Square	0.34
Observations	565

Table 9: R squared and number of observations of the regression for the distribution of onshore wind power based on data from the TU Delft Enipedia.

These results of the regression were used to distribute onshore wind. Cities can clearly be distinguished, such as the Ruhr area, Paris and Madrid. The north of Poland is windier than the south, the west coast of France and the Rhone valley can be distinguished, as well as the northeast of Spain around Lleida. The north of Germany gets more wind than the south and therefore more capacity is installed. This distribution of capacity gives a weight to each grid cell to improve the accuracy of the resulting production profiles compared with an even distribution of capacity over a country.

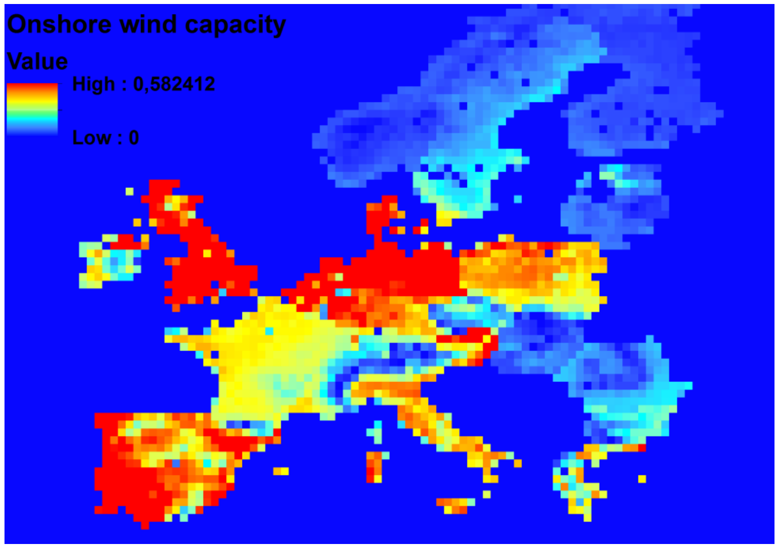

Figure 7: Distribution of onshore wind in 2050 for the Greenpeace scenario based on regression. The parameters determining the distribution are the elevation, wind resources, population density and roughness parameter. Red indicates high installed capacity, blue zero installed capacity. Capacity is in GW.

For offshore wind there was not enough data to perform a regression. The weather data is limited to the coast, which means that capacity needs to be distributed over the first few cells from the coast. For Germany this is not realistic since some of its offshore wind is installed very far from the shore. However, given the lack of offshore weather data this is the best approximation.

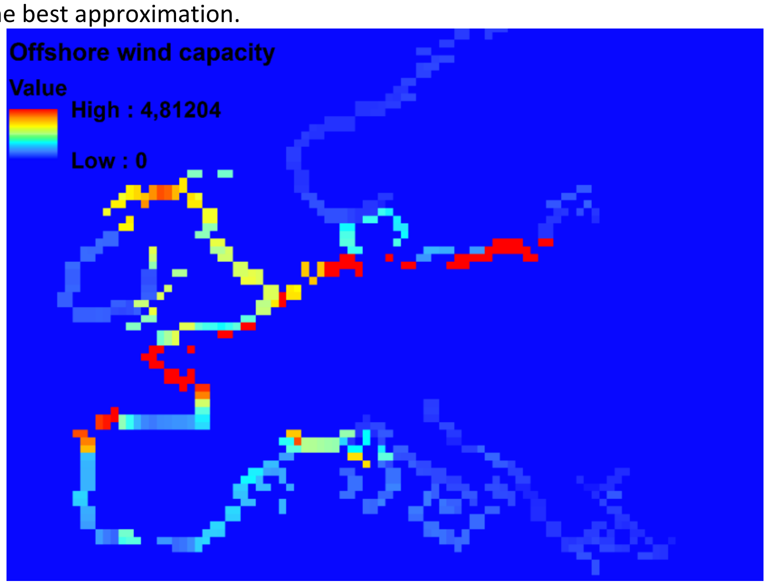

Figure 8: Distribution of offshore wind in 2050 for the Greenpeace scenario. Because of data constraints it is limited to the first 60-80 km offshore. The relation between wind resources and installed capacity was based on onshore wind. Capacity is in GW.

Cross-border correlations in wind and solar profiles

The country level capacity factor profiles are used for the optimization and to analyze the Greenpeace scenario, but the patterns can be studied on their own. The correlations in the solar and wind capacity factor profiles give us a first indication of the potential of interconnection to balance fluctuations in I-RES; low correlations mean that interconnection can smoothen the combined I-RES production profile. The capacity factor profiles of each country have been normalized by dividing the profile by their annual means. The following maps give the correlations with respect to the combined profile of Germany, France, Belgium and the Netherlands. Therefore these 4 countries are designated a correlation coefficient of 1. These profiles of these countries were combined since they have high correlation coefficients in I-RES production and it is assumed that these countries will be well interconnected by 2050.

The seasonal patterns are of course highly correlated. In the wind power patterns there are some areas which are less correlated with Northwest Europe: the Mediterranean countries and Scandinavia. The small negative correlation for Portugal is not significant, with a P-value of 0.2.

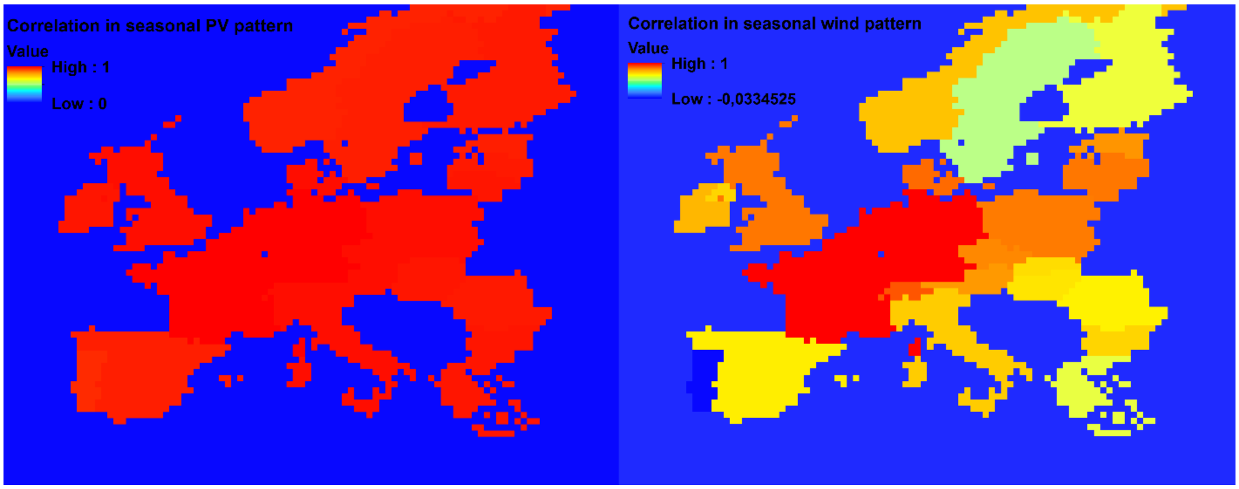

Figure 9: Seasonal correlation in the normalized PV (left) and wind production (right) profiles in Europe. Correlations are between European countries and Northwest Europe. Weather data is for the years 2002-2007. Red indicates a high correlation, blue a low correlation.

On shorter timescales wind power profiles are less correlated. The following figure gives the correlation in the wind profile during summer:

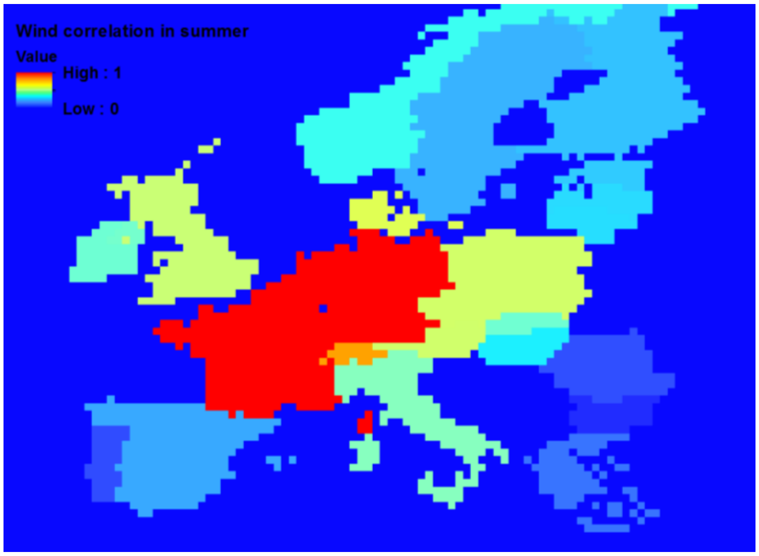

Figure 10: Correlations in the normalized wind power profile during summer between European countries and Northwest Europe. Weather data was taken for July and August for the years 2002-2007. Red indicates a high correlation, blue a low correlation. Based on 3-hourly profiles.

The correlation in summer shows a similar pattern to the seasonal correlation, with the Mediterranean and Scandinavia being less correlated with Northwest Europe than the UK and Eastern Europe.

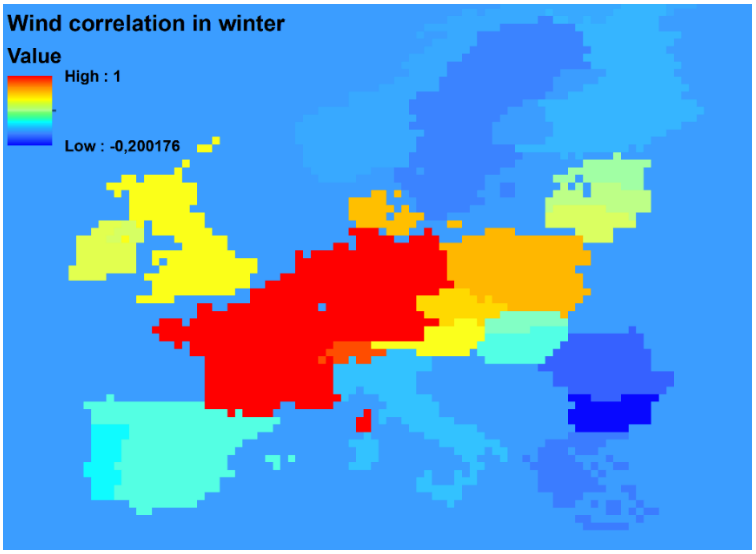

Figure 11: Correlations in the normalized wind power profile during winter between European countries and Northwest Europe. Weather data was taken for January and February of 2002-2007. Red indicates a high correlation, blue a low correlation. Based on 3-hourly profiles.

In winter, the correlations in the east-west direction are higher than in summer but the correlations in the north-south direction are as low as in summer. The negative correlation for Bulgaria is not significant. It can be concluded from these maps that wind patterns for countries with the same latitude are similar. Across the UK, Northwest Europe, Denmark and Poland wind is highly correlated. Scandinavia, the Mediterranean and Southeast Europe have correlation coefficients with Northwest Europe below 0.4, both in summer and in winter.
The results on the previous pages show the correlations between countries in the production profiles of either wind or solar power. However, there are also correlations between wind and solar power.
The following table shows the correlation between wind and solar power production for a few countries. Both wind and solar profiles have been normalized by dividing the profile by its mean value.

Country	Summer		Winter	
	Coefficient R	Significance P	Coefficient R	Significance P
Portugal	0.27	2.4E-33	0.082	0.00029
France	0.24	2.0E-27	0.045	0.049
Germany	0.18	3.3E-15	-0.045	0.048
Sweden	0.089	8.1E-05	-0.013	0.58

Table 10: Correlation between normalized wind and solar power production profiles for four countries in summer (left) and in winter (right). Weather data for July-August and January-February of 2002-2007 was used.

The table above shows that in summer, wind and solar power production are correlated. This correlation becomes weaker for countries farther to the north but remains significant. In winter, only Portugal has a small positive correlation between wind and solar power that is statistically significant. This means that heating of the atmosphere drives some of the winds during summer, which causes wind production peaks to coincide with insolation peaks.

Production from wind and solar power is not the same every year. The following table shows the standard deviation of the production from PV and wind power for the weather years of 2002 to 2012.

Country	PV	Wind
Portugal	0.053	0.060
France	0.042	0.11
Germany	0.056	0.097
Sweden	0.078	0.070
Europe	0.049	0.050

Table 11: Standard deviation in the normalized annual production of power from PV and wind for the weather years of 2002-2010. Normalization was done by dividing the annual production for each year by its mean value over 10 years.

From the table above it can be seen that the standard deviation in annual solar power production in Europe is 4.9%. For wind the value is 5.0%. However, the standard deviation for individual countries is in most cases higher than for Europe as a whole, meaning that these fluctuations average out when the production of many countries is combined. For PV the standard deviation in the production of individual countries is lower.

Greenpeace: 'Energy [R]evolution 2050'- analysis

Our model should yield results similar to the Energynautics grid study that was based on the Greenpeace scenario for 2050 since the same installed capacities per country were used. A comparison between a copper-plate Europe in the model and the Energynautics grid study is given in the following table:

Average of weather years 2010-2012	Copper plate		Energynautics	
Unit	TWh/yr	%	TWh/yr	%
Demand	4012	100	4012	100
I-RES production	1999	49.8	2014	50.2

Table 12: Share of wind and solar in Europe in the Energynautics grid study vs this thesis. Demand is for 2050, the weather years of 2010-2012 have been used. Demand of 2010-2012 has been scaled to match the demand by 2050 in the Greenpeace scenario.

Capacities (GW)		Wind-onshore	Wind-offshore	PV	CSP
Greenpeace	Copper plate	305	200	520	99

Table 13: Installed capacities in Europe in the Greenpeace advanced energy revolution scenario for 2050.

Results are comparable, which indicates that our capacity factor profiles are similar to those used in the Energynautics grid study. To understand the role if I-RES in this scenario, a more detailed look at the production patterns is required.

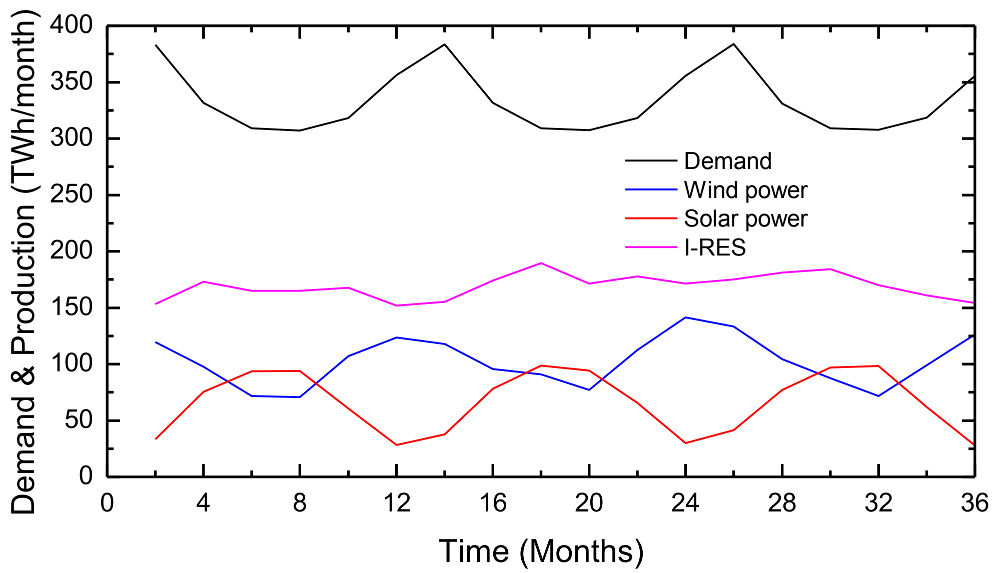

Figure 12: European seasonal demand and I-RES production profiles in 2050 based on the Greenpeace scenario. The weather years of 2010-2012 have been used, demand of 2010 to 2012 has been scaled to match the demand by 2050 in the Greenpeace scenario. Demand and production is in TWh per month.

In the figure above the seasonal demand and production profiles are given for three weather years (2010-2012). Three observations can be made immediately:

1. Demand is the smoothest of these three, with the summer/winter demand ratio of 0.8.
2. Solar production varies the most throughout the year, with a summer/winter ratio over 3.3.
3. Wind production is correlated with demand, but wind varies more than demand with a summer/winter ratio of 0.5-0.6.

It is apparent that a system cannot rely on PV as the backbone without large amounts of seasonal storage. The same applies to wind, because the decrease in production of wind in the summer is larger than the decrease in demand. The seasonal ideal mix would consist of a majority of wind, supplemented with some solar PV to fill the gap in summer. The peak in wind production in November-December is a few months before the peak in demand in January and February. Wind production varies more from one year to another than solar production.

The seasonal patterns by no means tell the whole story. Wind and solar production and electricity demand show variation on hourly timescales.

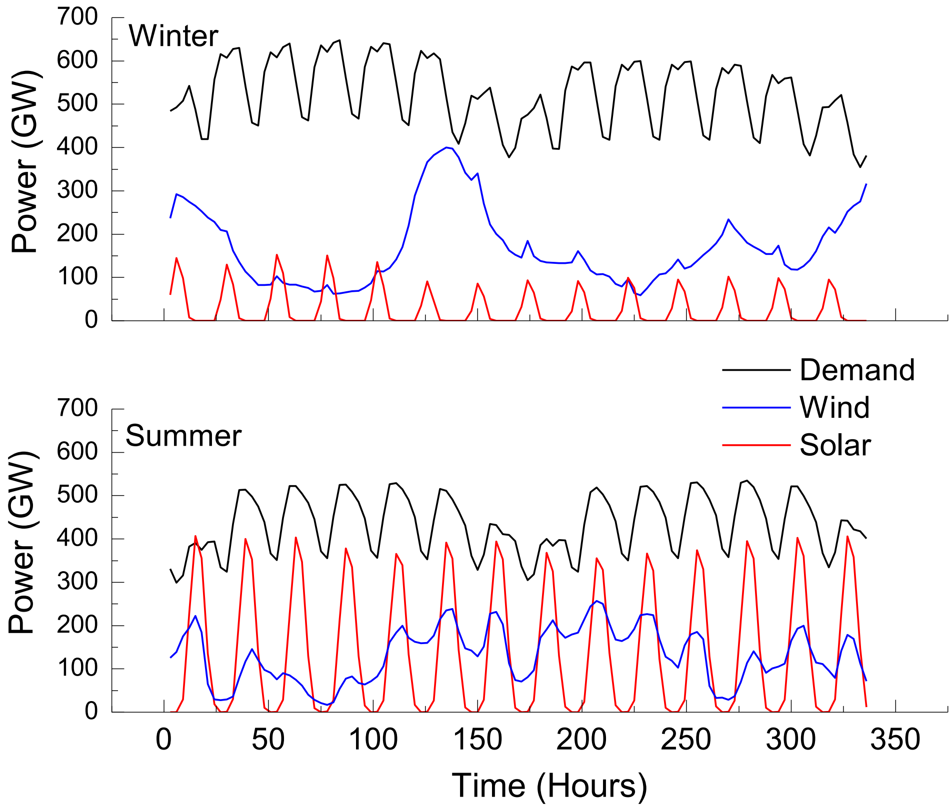

Figure 13: Demand and I-RES production in Europe during two winter weeks (top) and two summer weeks (bottom), based on the Greenpeace scenario for 2050. The weather and demand data is for 2012. Demand has been scaled to match the demand in 2050 for the Greenpeace scenario.

The figure above shows a more detailed picture of demand and production of intermittent renewables in summer and winter. In winter, production of wind is higher than in summer and has higher maxima. The typical time scale of windy periods is a few days which means that at times there is excess power during the night when demand is low. There is a diurnal pattern in the wind production but this is only +-10 % of production whereas during windy periods of a few days production increases with 300% or more.

Production of solar energy is low, but of the same order of magnitude as the diurnal variation in demand, so in this scenario solar PV can provide daytime peak demand in winter. However, the time window of PV production is a few hours narrower than the peak in demand. This makes the evening and morning difficult as solar PV is poorly matched with the evening peak, which is a big problem in winter.

During summer, solar production dominates the system and the variation in production far exceeds the daily variation in demand. Solar production is fairly constant across Europe on this timescale, with a variation between days of +-10 percent during these two weeks in summer. The evening peak in demand has almost disappeared, but solar production still ramps down a couple of hours before demand. Obviously the system needs some form of back up during the night.

Wind cannot contribute much to compensate this pattern since production is much lower than in winter and wind power in summer has a strong diurnal pattern. The diurnal peaks are 40GW in size which is significant compared with an average production of 140 GW.

Because the diurnal variation in wind and solar power are correlated, the problem of excess power around noon in summer is made worse. This diurnal wind pattern has been described in other studies, such as 'Least-cost options for integrating intermittent renewables in low-carbon power systems' (Brouwer, Broek, & Zappa, 2015). In this study the strong afternoon peaks in wind production during summer were also observed. These patterns are well documented in meteorology (Barthelmie, Grisogono, & Pryor, 1996).

In the Greenpeace scenario the large amount of solar power creates problems during summer even in a copper-plate Europe, because of the low summer demand, combined with large amounts of solar power and the diurnal pattern in wind power. During winter, nearly 600 GW of backup capacity is needed at times when there is little wind because of the high peak demand during winter. This backup capacity needs to be flexible since there are moments when there is a large amount of wind during the night and the remainder is less than 20 GW (hours 140-150 in Figure 13).

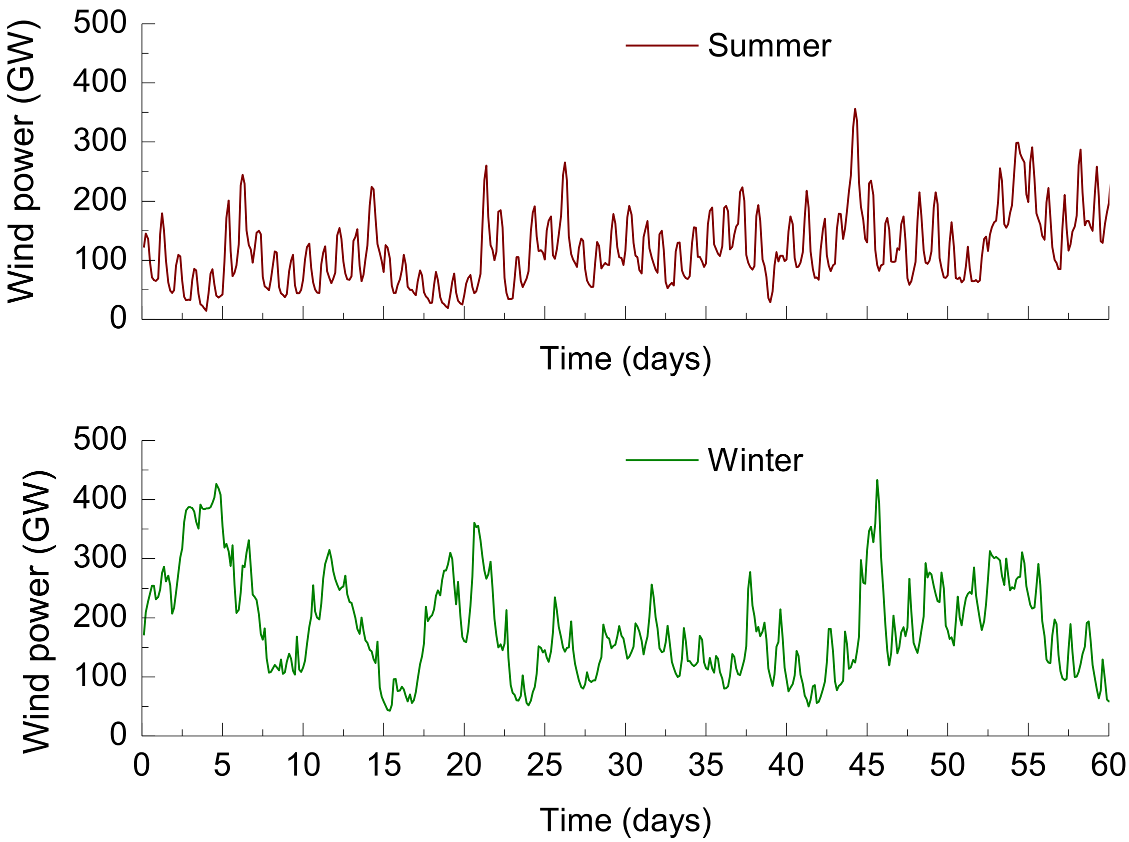

Figure 14: Wind power production in Europe in the Greenpeace scenario for 2050 in summer (top) and in winter (bottom). Weather data of July-August and January-February of 2012 have been used for summer and winter, respectively.

This figure shows wind power production over longer time periods. The diurnal pattern in summer can clearly be distinguished. Apart from the diurnal cycle it is smoother than wind power during winter. Wind power during winter has typical peak periods of 4-8 days, a longer duration than in the previous figure. Minimum production is only 41 GW.

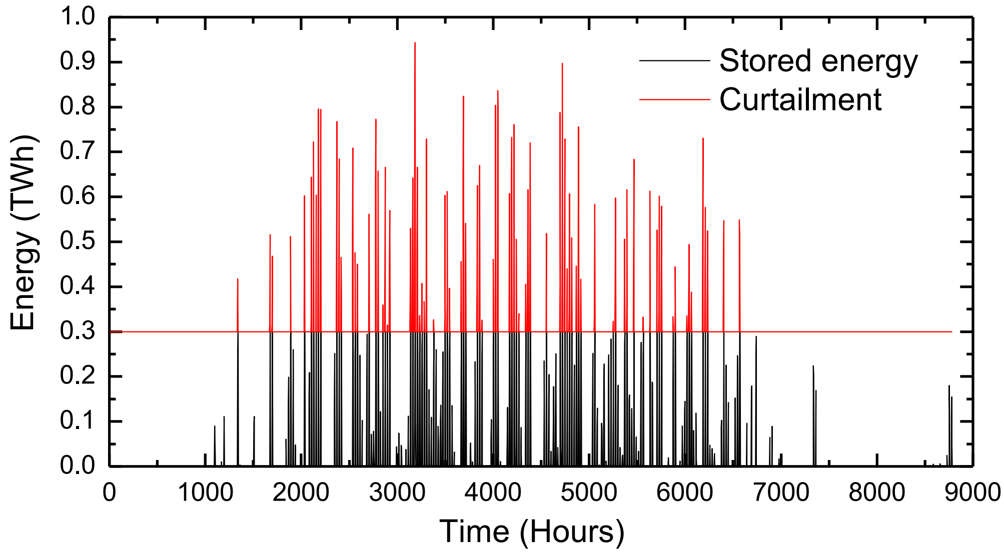

Figure 15: Storage and curtailment in the Greenpeace scenario for 2050 in a copper plate Europe. Weather data for 2012 was used. The storage volume of 0.3 TWh was chosen to match the share of I-RES in the Greenpeace scenario.

The excess in I-RES production during summer is reflected in the storage and curtailment. In this figure the storage and curtailment are given. The storage capacity of 0.3 TWh was chosen so that the penetration of I-RES in this thesis agrees with the results of the Energynautics grid study. This storage volume is not very large, compared for instance with the maximum potential pumped storage volume in Norway of over 80 TWh (SRU, 2011). The required power is a bigger problem, with production from storage and filling of storage of 100 GW being common. The discharge time of 3 hours is in the range of batteries, flow batteries and compressed air energy storage (IEC, 2011).

Sometimes excess wind power is stored during winter. But storage is mainly used in summer to absorb peaks in solar production. These peaks last during the day and the stored energy is discharged during the night. Energy needs to be curtailed for a few days in a row if discharge during the night is not possible due to high wind power production. In summer around noon not just solar power is curtailed, but because the diurnal pattern of wind and insolation are correlated wind power is curtailed as well.

So far production time series have been analyzed, but the rest of the power system needs to adjust to the *fluctuations* in production from I-RES.

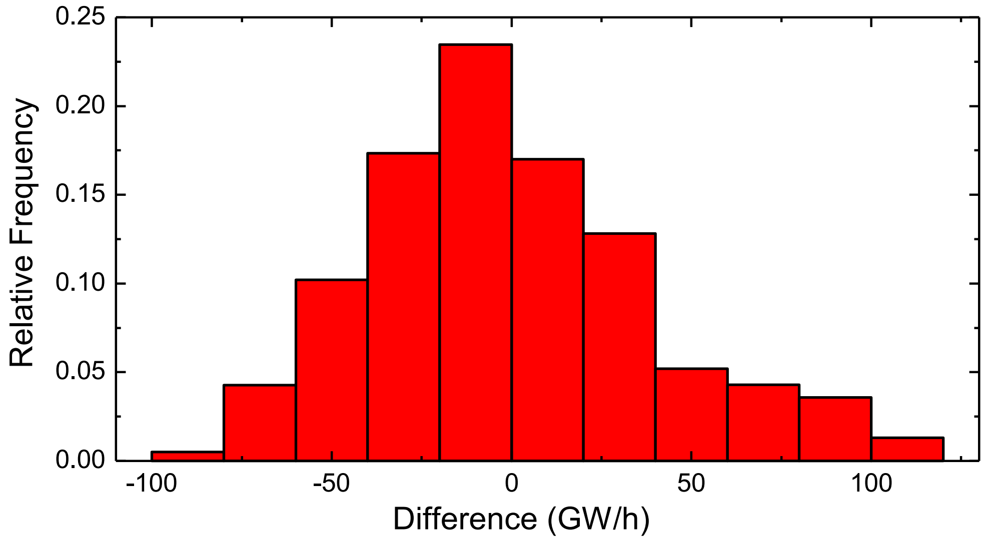

Figure 16: Histogram of fluctuations between 3-hourly time steps of the net remainder in the Greenpeace scenario for 2050, based on the weather years of 2010-2012 for a copper plate Europe.

As can be seen in this figure, the histogram of fluctuations in the net remainder is not symmetrical. Large (>50GW/h) increases in the net remainder are often seen. This corresponds with a large decrease in the production of I-RES and at the same time a constant or increasing demand. This occurs during the evenings when solar power output decreases and demand increases simultaneously.

Indicators

To compare a copper plate Europe with a European system without interconnection storage was allocated to each country based on their annual demand. Total storage volume is the same for both variants at 0.3 TWh. The results are given in the following table:

Per annum	Copper plate		No interconnection	
Unit	TWh/yr	%	TWh/yr	%
Demand	4012	100	4012	100
Renewable production	1999	49.8	1675	41.7
Forced Exchange	303	7.5	0.0	0.0
Total net Remainder	2018	50.3	2720	67.8

Table 14: Key indicators in the Greenpeace scenario for 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario.

Removing interconnection decreases the share of I-RES from 49.8 to 41.7%. This is caused by the increase in curtailment. This is reflected in the forced exchange, which is similar in magnitude as the reduction in production from I-RES.

Per annum	Copper plate		No interconnection	
Unit	TWh/yr	%	TWh/yr	%
Renewable production	1999	100.0	1675	100.0
Curtailed Energy	28	1.41	352	21.0
Curtailed solar	17	0.83	145	8.6
Curtailed wind	12	0.58	208	12.4
Total Stored Energy	34	1.68	31	1.8

Table 15: Key indicators in the Greenpeace scenario for 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario.

The curtailed energy with no interconnection is similar in magnitude to the forced exchange, it is about 20% of renewable production. More wind than solar energy is curtailed if countries are not interconnected, but relative to production solar energy is curtailed 10% more often than wind power. For a copper plate Europe curtailment is very low, and mostly solar power is curtailed.

	Copper plate	No interconnection
I-RES Capacity credit	12.5% of peak demand	4.6% of peak demand
Wind/Solar capacity	47.6% / 52.4 %	47.6% / 52.4 %
Wind/Solar production	61.1% / 38.9%	61.1% / 38.9%
Storage capacity	0.3 TWh	0.3 TWh

Table 16: Key indicators in the Greenpeace scenario for 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Capacity credit is based on a peak demand of 671GW.

The capacity credit of wind and solar power in the system, as a percentage of peak demand, decreases dramatically when countries are poorly interconnected. In the Greenpeace scenario, going from a system without interconnection to a copper plate system increases the capacity credit of I-RES by over 170%, increases the share of I-RES with almost 20% by reducing curtailment, improves the utilization of storage and reduces the total net remainder by 26%.

Optimized capacity distributions

The benefits of interconnection are obviously enormous in systems with a high share of intermittent renewables. But the Greenpeace scenario can be improved upon using the optimization where the total net remainder is reduced. The first optimizations are without constraints on the total installed capacity. Later the constraint that the total installed capacity of both wind and solar power should be equal to the installed capacity in the Greenpeace scenario is added.

Unconstrained optimization

3-hour

This optimization is based on 3-hour capacity factor and demand profiles. The optimization converged and favored wind capacity, particularly offshore wind as can be seen in the resulting capacity mix.

Capacities (GW)		Wind-onshore	Wind-offshore	PV	CSP
3-h optimized	Copper plate	809	689	474	0.0094
3-h optimized	No interconnection	568	349	807	88
Greenpeace	Copper plate	305	200	520	99

*Table 17: Optimal installed capacities 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimization is based on the **3-hourly** profiles for both a copper plate Europe and for Europe without interconnection.*

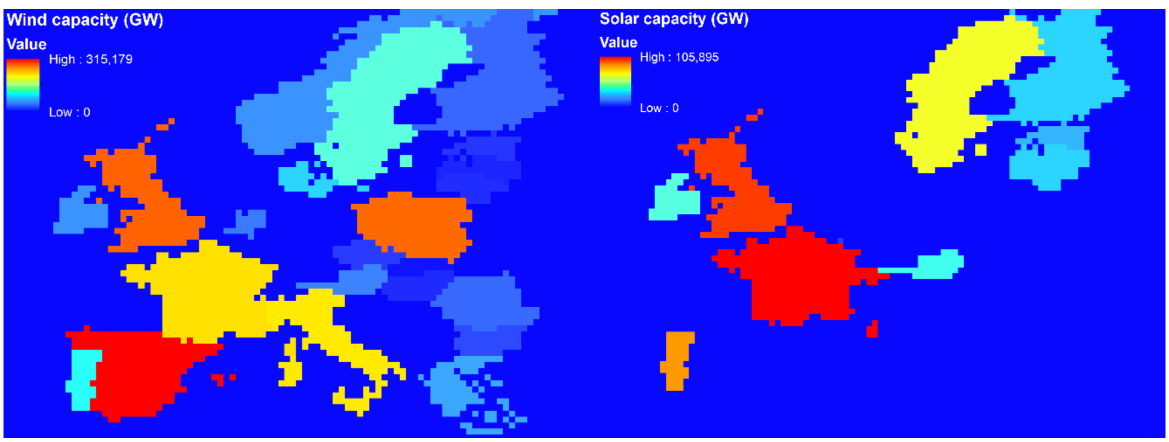

Figure 17: 3-h optimized total wind and solar capacity per country based on a copper plate Europe. In Spain, 200GW is installed onshore and 100GW offshore.

The wind profiles of countries is the south of Europe are well matched to the demand profile. Offshore wind which has a more constant output than onshore wind is favored. Most of the wind power installed in Poland, the UK and France is offshore. The profile of wind in southern European countries combined with the solar profile of France and the UK follows the European demand profile very well. Germany's production patterns are not optimal so little to no capacity is installed there. The 200 GW onshore wind installed in Spain corresponds to 0.4 MW/km^2, which is four times the density of wind power installed in Denmark in 2014 (Danish Wind Energy Association, 2015).

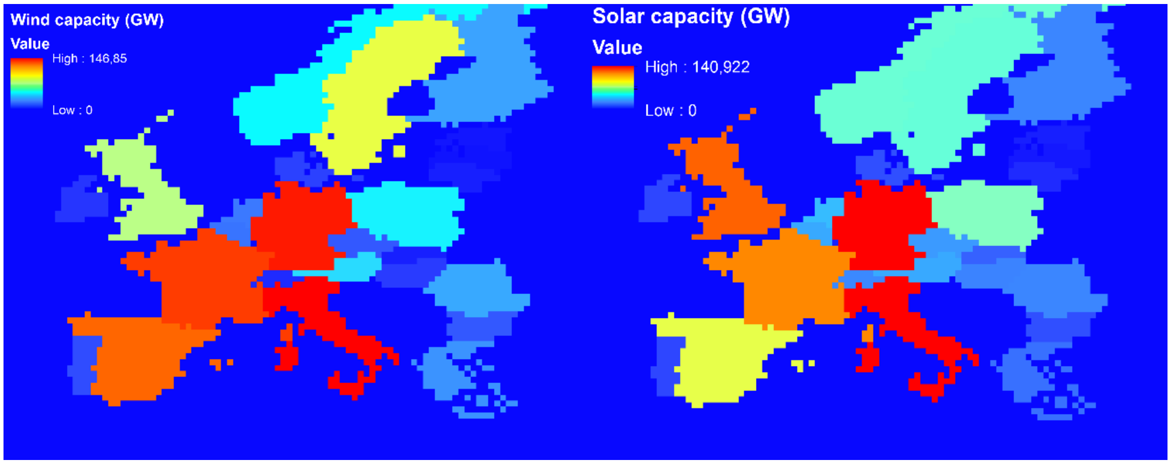

Figure 18: 3-h optimized total wind and solar capacity installed per country for Europe with no interconnection.

The optimization with no interconnection leads to high installed solar capacities. Relatively little wind is installed in the UK, because it has a high capacity factor and installing more wind would lead to curtailment. The same is observed for solar power in Spain, relatively little is installed because more capacity would lead to higher curtailment.

Both optimizations increase the share of intermittent renewables in annual production. Without interconnection, the amount of offshore wind is decreased and the amount of solar PV increases.

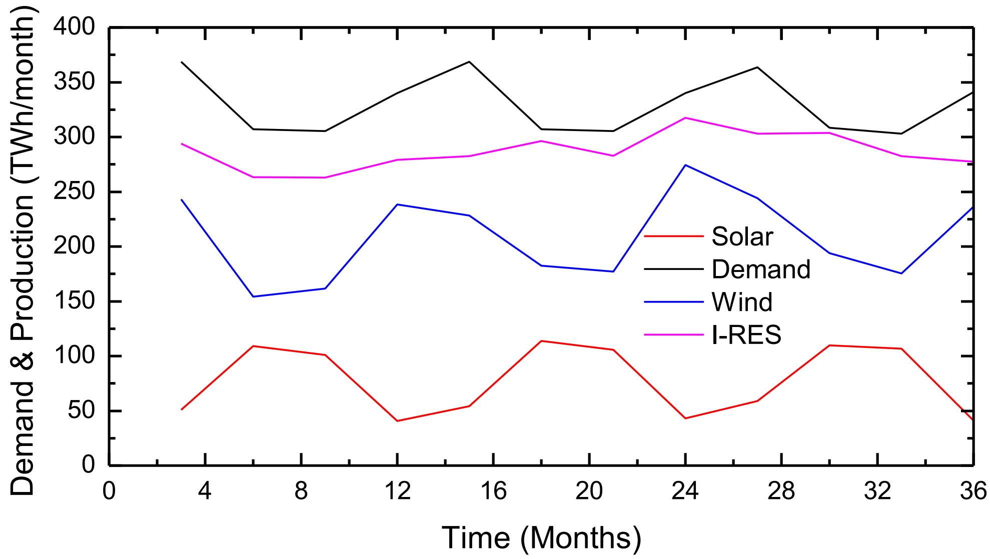

Figure 19: Seasonal demand and I-RES production profiles in Europe based on the optimized capacity distribution. Weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario have been used. Optimization is based on the ***3-hourly*** *profiles for a copper plate Europe.*

Decreasing the objective function means that the share of I-RES increases. This can be seen in the previous figure where the seasonal profiles for weather years 2010-2012 are displayed for the copper plate optimization. The optimal mix has a share of I-RES of 80%, incorporating any more I-RES increases the objective function. Three quarters of the production from I-RES comes from wind, with solar power to compensate for the decrease in supply of wind power during summer. Since this optimization was based on 3-hourly profiles the profiles should be studied in detail.

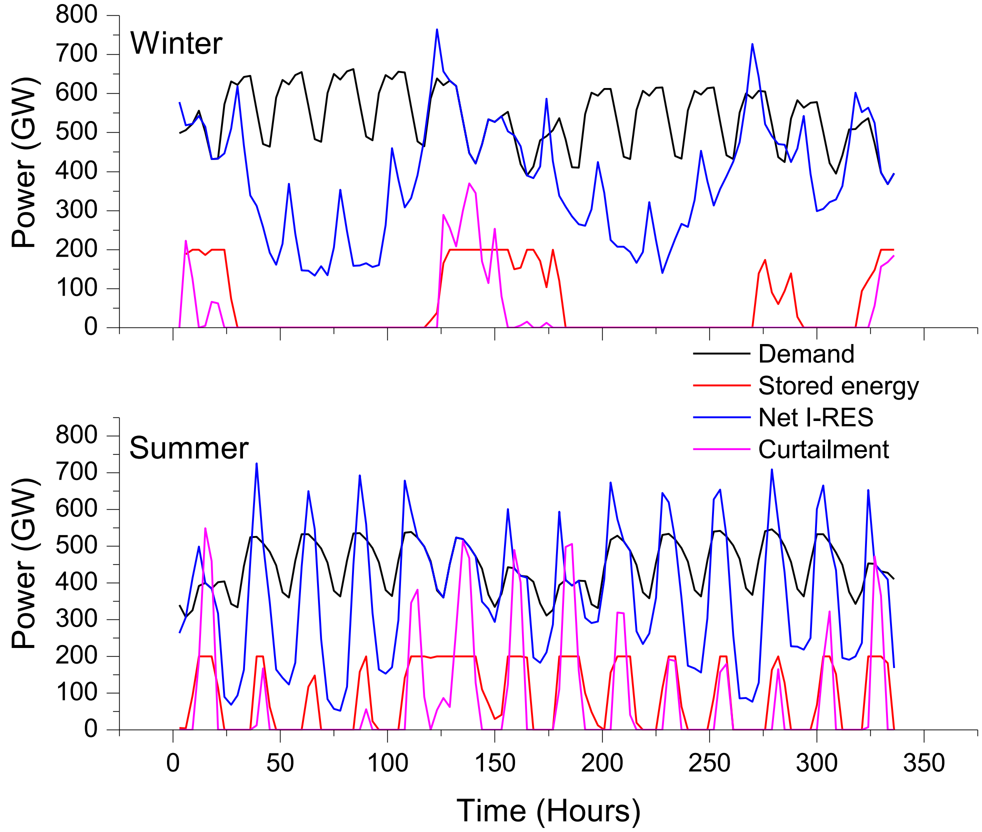

*Figure 20: Demand, I-RES production, stored energy and curtailment during two winter weeks (top) and two summer weeks (bottom) in a Europe based on the optimized capacity distribution. Weather year is 2012 and demand is for 2012, scaled to match the demand in 2050 in the Greenpeace scenario. Optimization is based on **3-hourly** profiles for a copper plate Europe. Stored energy level of 200 GW corresponds with 0.6TWh since the time step is 3 hours.*

In the previous figure the same weeks that were shown for the Greenpeace scenario are shown again for the optimized copper plate Europe. The diurnal cycle is more pronounced since the share of I-RES is higher. The same 2-3 day cycle in wind power that was observed earlier is visible. In winter, storage is typically filled in 6 hours and curtailment follows immediately. Storage is full 30% of the time and is typically full for 24 to 48 hours.
In summer, peaks around noon have to be curtailed in 93% of the days, with curtailment lagging a few hours behind storage. Over 90% of the time, the storage is emptied during the night but sometimes (hours 100-150) the storage cannot empty during the night and this increases the curtailed energy the next day. Again, curtailed energy is not just solar but also wind which also has a diurnal pattern.

Clearly, solar power needs high power storage to match supply with demand and cover the evening peaks. For wind power high power storage helps the integration in the grid, but the utilization is much lower because the storage is either full or empty for multiple days in a row. The total net remainder, which is the objective function in the optimization, is strongly affected by the amount of high power storage, mostly because of solar power.

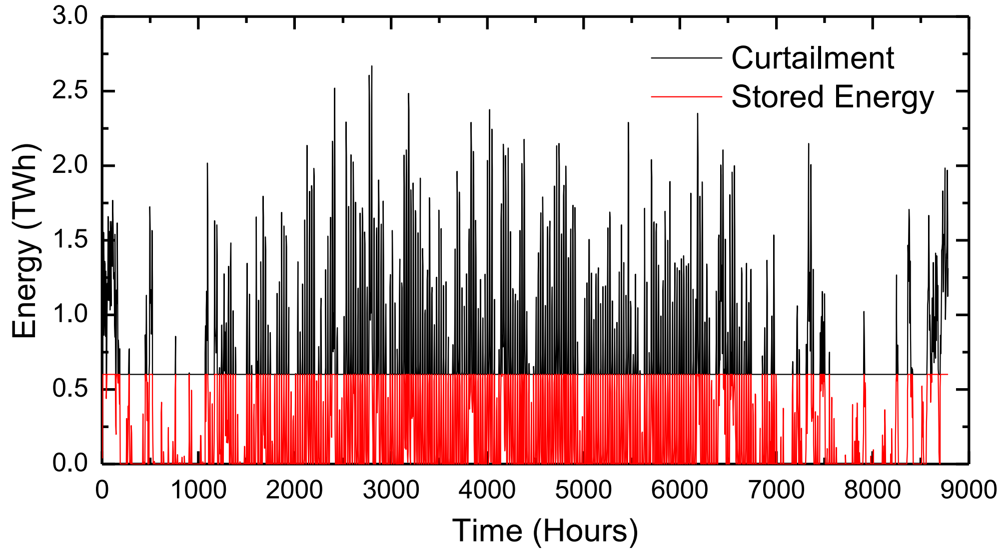

*Figure 21: Storage and curtailment for the optimized capacity distribution in a copper plate Europe in 2050. Weather data for 2012 and demand data for 2012 scaled to match the demand in 2050 was used. Optimization is based on **3-hourly** profiles for a copper plate Europe.*

These results are reflected in the graph for storage and curtailment. Even in an optimized and fully interconnected system, daytime peaks of solar and wind power need to be curtailed. Because the share of wind power has increased compared with the Greenpeace scenario, wind is stored and curtailed during winter as well.

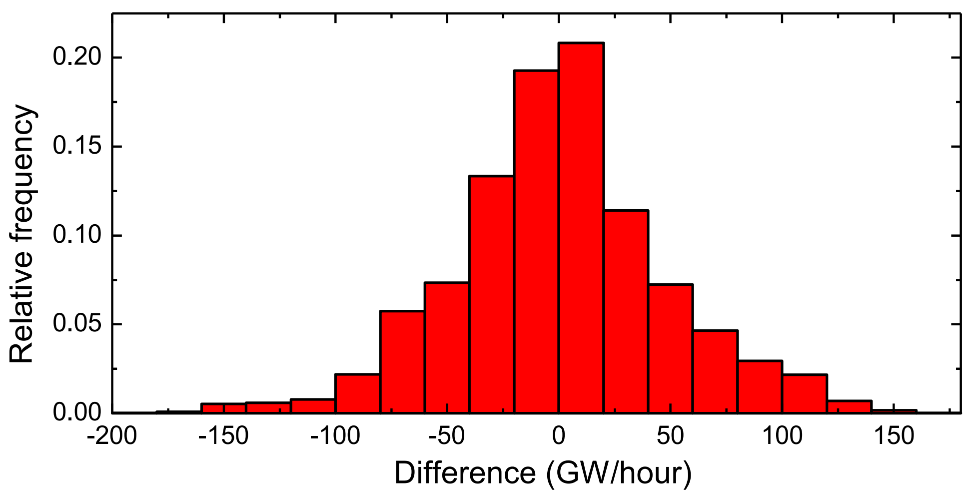

*Figure 22: Histogram of fluctuations of the net remainder for the optimized capacity distribution. Weather years of 2010-2012 have been used and the demand of 2010-2012 was scaled to match the Greenpeace scenario for 2050. Optimization was based on the **3-hourly** profiles for a copper plate Europe.*

Because the amount of capacity installed is much higher than in the Greenpeace scenario, the distribution of the differences in the net remainder is much wider, but the bulk of the distribution is still between -100 and +100 GW/h. An important thing to note is that the distribution is more symmetric than the Greenpeace scenario, but extreme events often have a negative value for the differential in the net remainder. This means that there is a sudden increase of production from I-RES relative to demand (wind at night).

Seasonal

Capacities (GW)		Wind-onshore	Wind-offshore	PV	CSP
Seasonal optimized	Copper plate	1053	521	640	96
Seasonal optimized	No interconnection	701	486	1047	134
Greenpeace	Copper plate	305	200	520	99

Table 18: Optimal installed capacities 2050, based on weather years of 2002-2012 and demand years of 2002-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimization is based on the seasonal profiles for both a copper plate Europe and for Europe without interconnection.

The previous optimization was based on 3-hourly weather data and 3-hourly wind and solar profiles. If there is sufficient storage the supply can follow demand on short timescales. But during longer periods in summer or winter, there could still be a shortage or an excess of energy. This is why an optimization was done based on the seasonal demand profile and the seasonal wind and solar profiles. This further increases the amount of I-RES in the optimization. In a copper plate Europe, onshore wind is favored over offshore wind with an offshore/onshore ratio similar to the Greenpeace scenario. Again, removing interconnection leads to increased total installed PV capacity because wind power peaks would have to be curtailed.

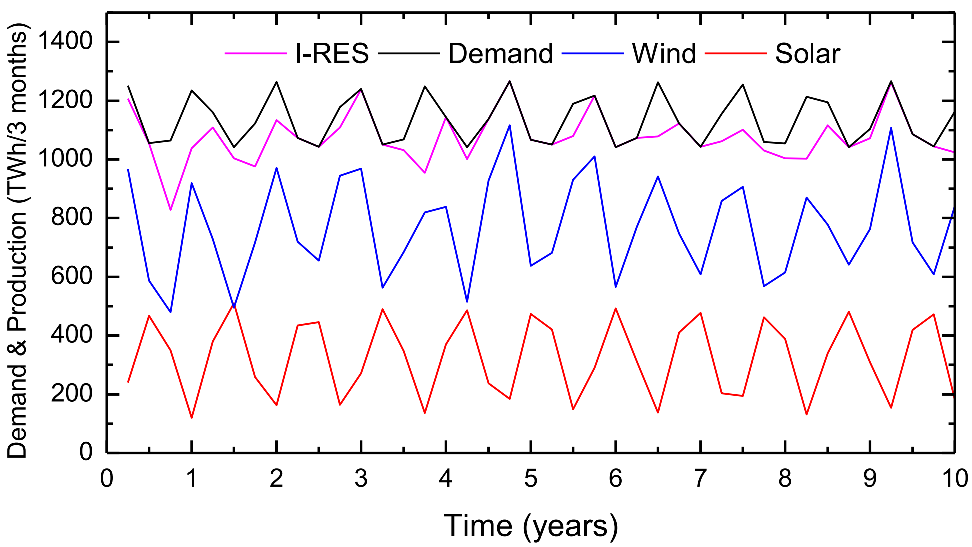

*Figure 23: Seasonal demand and I-RES production profiles in Europe based on the optimized capacity distribution. Weather years of 2002-2012 and demand years of 2002-2012 scaled to match the demand in 2050 in the Greenpeace scenario have been used. Optimization is based on the **seasonal** profiles for a copper plate Europe. Demand and production is in TWh per quarter.*

Using the seasonal profile means that all fluctuations on shorter timescales than 3 months are smoothed. This is effectively the same as having a large amount of storage, enough so that all fluctuation on short timescales average out. The storage volume was set to 1.4 TWh because the 3-hour profiles with 1.4 TWh of storage yielded the same results for I-RES penetration as the seasonal profile without storage when applied to the seasonal optimal capacities.

This increased storage volume has the effect that more I-RES can be integrated in the system without increasing the total net remainder. As can be seen in the figure above, the seasonal production from I-RES is very well matched to the seasonal demand profile. There are almost no shortages in summer because solar power output fluctuates little from year to year, but during winter not all peaks in demand can filled with I-RES because wind power output during winter has strong fluctuations from year to year.

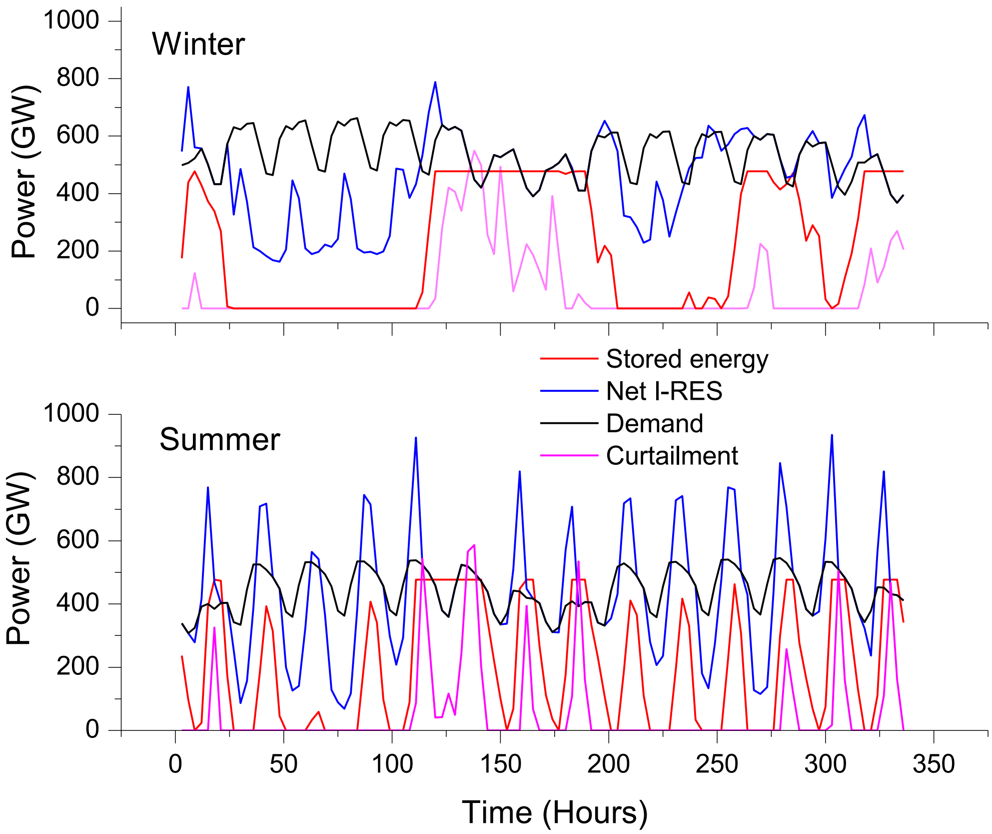

Figure 24: Demand, I-RES production, stored energy and curtailment during two winter weeks (top) and two summer weeks (bottom) in Europe based on the optimized capacity distribution. Weather year is 2012 and demand is for 2012, scaled to match the demand in 2050 in the Greenpeace scenario. Optimization is based on ***seasonal*** *profiles for a copper plate Europe.*

In this figure the winter and summer weeks are plotted again, this time for the seasonal optimal installed capacities. The patterns are similar to those of the 3-hour optimized mix. The biggest difference is in the storage of wind power, where storage is now full almost 50% of the time. The large storage volume is benefits solar power during summer and only on 60% of the days energy has to be curtailed compared with over 90% of the days for the 3-h optimal mix.

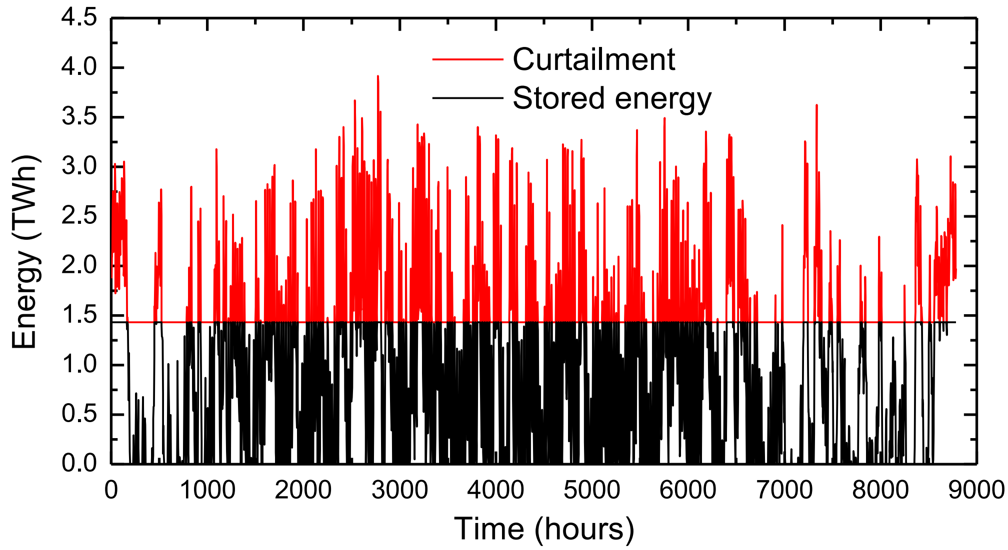

Figure 25: Storage and curtailment for the optimized capacity distribution in a copper plate Europe in 2050. Weather data for 2012 and demand data for 2012 scaled to match the demand in 2050 was used. Optimization is based on ***seasonal*** *profiles for a copper plate Europe.*

In the figure above storage and curtailment has been shown for the seasonal optimal mix in copper plate Europe. The storage volume is 1.4 TWh which is over twice as much as in the 3-h optimal mix (0.6 TWh). The total energy capacity is very high for such a high power storage volume which can charge or discharge within 3 hours. Energy is mostly curtailed during summer.

Comparison

Now that the main results of the optimization have been reviewed, the optimization for a copper plate Europe is compared with the optimization where countries are not interconnected. The seasonal optimization is compared with the 3-h optimization.

Per annum	3-hour optimization				Seasonal optimization			
	Copper plate		No interc.		Copper plate		No interc.	
Unit	TWh/yr	%	TWh/yr	%	TWh/yr	%	TWh/yr	%
Demand	4009	100	4009	100	4009	100	4009	100
I-RES production	3182	77.9	2499	62.3	3917	97.7	3495	87.2
Forced Exchange	188	4.7	0.0	0.0	1356	33.8	0.0	0,0
Total net Remainder	1361	33.9	1458	36.4	1030	25.7	1670	41.7

Table 19: Key indicators for the optimized capacity distributions in 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimizations for copper plate Europe and Europe without interconnection, based on 3-hourly and seasonal profiles are compared.

For the 3-hour optimal mix, the value of the objective function for the copper plate Europe is 6.7% lower than with no interconnection, while the share of I-RES is 25% higher. The bigger the share of intermittent renewables, the bigger the benefits of interconnection. The optimization also reduced forced exchange, which is lower than it was in the Greenpeace scenario.

The seasonal optimal mix leads to similar penetration levels of I-RES with and without interconnection, but the effect of interconnection on the total net remainder is bigger than in the 3-hour optimal mix. The forced exchange in the seasonal optimal mix is a factor 7 higher than in the 3-hour optimal mix, because capacity is distributed unevenly over Europe.

Per annum	3-hour optimization				Seasonal optimization			
	Copper plate		No interc.		Copper plate		No interc.	
Unit	TWh/yr	%	TWh/yr	%	TWh/yr	%	TWh/yr	%
I-RES production	3182	100	2499	100	3917	100	3495	100
Curtailed Energy	414	13.0	290	11.6	506	12.9	635	18.2
Curtailed solar	151	4.8	109	4.4	143	3.7	177	5.1
Curtailed wind	262	8.2	181	7.2	363	9.3	458	13.1
Total Stored Energy	154	4.8	111	4.4	312	8.0	506	14.5

Table 20: Key indicators for the optimized capacity distributions in 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimizations for copper plate Europe and Europe without interconnection, based on 3-hourly and seasonal profiles are compared.

For the 3-hour optimized distribution the higher share of I-RES in the copper plate system only slightly raise the percentage of power that needs to be curtailed. The utilization of storage improves when countries are interconnected. The seasonal optimal mix without interconnection has far higher curtailment than the 3-hour optimal mix. The large storage volume of the seasonal optimal mix reduces curtailment of solar power relative to the total curtailment.

The following table shows the large storage requirements of the seasonal optimal mix in the case of no interconnection, compared with the 3-hour optimal mix. Both with and without interconnection, the amount of curtailed wind power increases compared with the 3-hourly optimized mix.

	3-h optimization		Seasonal optimization	
	Copper plate	No interc.	Copper plate	No interc.
I-RES capacity credit	26.1% of peak demand	7.1% of peak demand	43.8% of peak demand	8.0% of peak demand
Wind/Solar capacity	76% / 24%	50% / 50%	68% / 32%	51% / 49%
Wind/Solar production	74% / 26%	62% / 38%	76% / 24%	61% / 39%
Storage capacity	0.60 TWh	0.60 TWh	1.43 TWh	3.43 TWh

Table 21: Key indicators for the optimized capacity distributions in 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimizations for copper plate Europe and Europe without interconnection, based on 3-hourly and seasonal profiles are compared. Capacity credit is based on a peak demand of 671GW.

One of the more striking results is that the I-RES capacity credit for the seasonal optimal mix compared with the 3-hour optimal improved by 68% in the copper-plate Europe, whereas for individual countries it barely improved. This means that storage without interconnection has a small effect on the capacity credit of intermittent renewables, but with interconnection the storage can increase the capacity credit of intermittent renewables.

The ratio of wind to solar power in production shows that the copper plate optimization favors wind power in both cases. Without interconnection the ratio of wind to solar in production decreases.

Constrained optimization

The Greenpeace scenario gives I-RES capacities per country. This capacity distribution results has been based on projections for cost developments by Greenpeace so optimization can decrease the objective function. This time the total capacity of wind and solar power are constrained, which means that both the total wind capacity and the total solar capacity need to be the same as in the Greenpeace scenario.

The optimization decreases the total net remainder. This is done by moving wind to the countries with the highest capacity factors and moving wind offshore as much as possible, as can be seen from the intermittent renewable production and the wind to solar production ratio.

Capacities (GW)		Wind-onshore	Wind-offshore	PV	CSP
Greenpeace	Copper plate	305	200	520	99
Constrained optimization	Copper plate	157	348	508	111

Table 22: Optimal installed capacities in 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimization is based on the 3-hourly profiles for a copper plate Europe, with the constraint that the total capacity of both wind and solar must remain equal to that in the Greenpeace scenario.

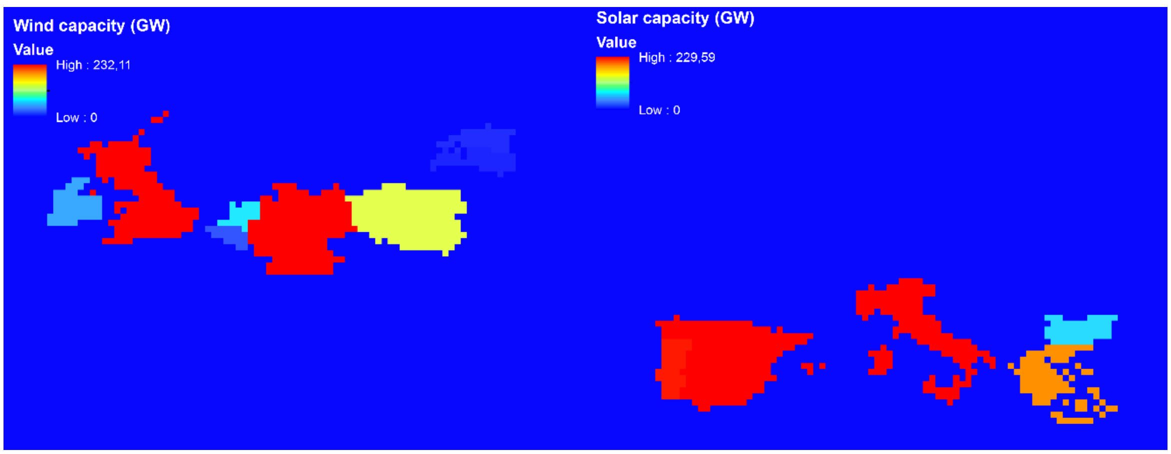

Figure 26: 3-h optimized installed capacities for a copper plate Europe when the total wind and solar capacity is constrained to the values in the Greenpeace scenario.

This optimization moves wind and solar power to the countries with the highest capacity factors, in order to match I-RES supply with the demand profile. Wind power is mostly installed offshore.

Per annum, copper plate	Greenpeace		Optimized	
Unit	TWh/yr	%	TWh/yr	%
Demand	4012	100	4012	100
Renewable production	1999	49.8	2644	65.9
Forced Exchange	303	7.5	947	23.6
Total net Remainder	2018	50.3	1683	41.9

Table 23: Key indicators for the optimized capacity distribution in 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimization is based on the 3-hourly profiles for a copper plate Europe, with the constraint that the total capacity of both wind and solar must remain equal to that in the Greenpeace scenario.

The optimization reduces the objective function dramatically. This has a large effect on the interconnection requirements, with the exchanged energy tripling compared with the Greenpeace scenario.

Per annum, copper plate	Greenpeace		Optimized	
Unit	TWh/yr	%	TWh/yr	%
Renewable production	1999	100,0	2644	100.0
Curtailed Energy	28	1.4	97	3.7
Curtailed solar	17	0.8	47	1.8
Curtailed wind	12	0.6	50	1.9
Total Stored Energy	34	1.7	101	3.8

Table 24: Key indicators for the optimized capacity distribution in 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimization is based on the 3-hourly profiles for a copper plate Europe, with the constraint that the total capacity of both wind and solar must remain equal to that in the Greenpeace scenario.

Even though exchange and storage have tripled, the amount of energy curtailed still increases in the optimized distribution compared with the Greenpeace scenario.

Copper plate	Greenpeace	Optimized
I-RES capacity credit	12.5% of peak demand	23.8% of peak demand
Wind/Solar capacity	48% / 52%	48% / 52%
Wind/Solar production	61% / 39%	66% / 34%
Storage capacity	0.30 TWh	0.60 TWh

Table 25: Key indicators for the optimized capacity distribution in 2050, based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimization is based on the 3-hourly profiles for a copper plate Europe, with the constraint that the total capacity of both wind and solar must remain equal to that in the Greenpeace scenario. Capacity credit is based on a peak demand of 671GW.

However, the capacity credit of I-RES almost doubles by redistributing capacity, mostly because more wind is installed offshore where minima in production are higher than onshore.

Storage

Finally, the optimization was carried out on a 3-hourly basis for a copper plate Europe for a range of volumes of storage. Each optimization converged to an optimum with a certain mix of wind and solar power in production. The resulting ratio of wind to solar power is given in the following figure.

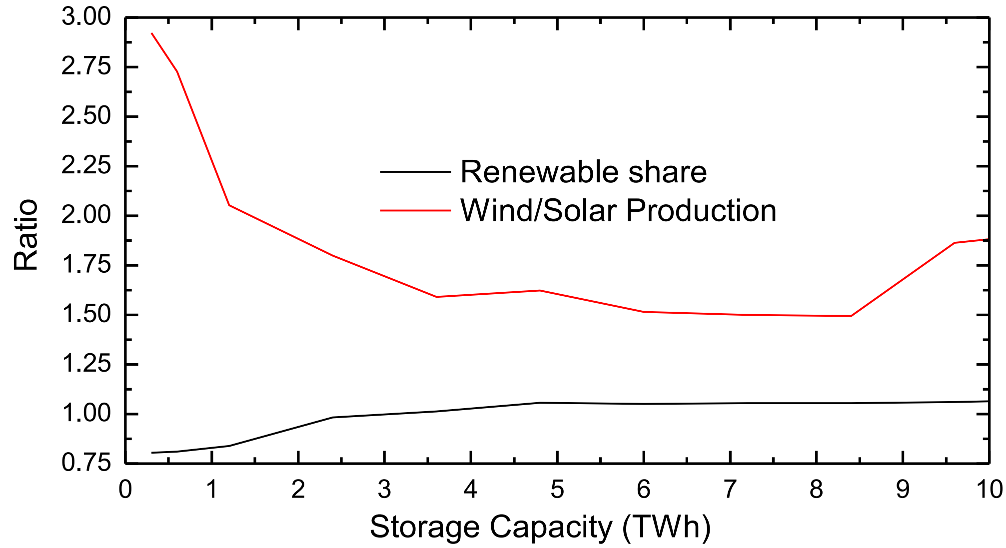

Figure 27: Optimal ratio of wind to solar power production and share of I-RES as a function of the volume of storage. Based on weather years of 2010-2012 and demand years of 2010-2012 scaled to match the demand in 2050 in the Greenpeace scenario. Optimization is based on the 3-hourly profiles for a copper plate Europe

It can be seen that high power storage capacity favors solar power and the optimal penetration of I-RES increases with increasing storage capacity. When the storage capacity becomes of the order of daytime peaks during summer (2 TWh), the effect of installing more storage on the optimal mix decreases. The wind to solar ratio levels off at 60% wind and 40% solar.

This behaviour can be predicted from the storage and production profiles in the 3-hour optimal mix. During winter when wind dominates the utilization of high power storage is poor because cycles last a few days, whereas in the summer the storage volume fully charges and discharges over 90% of the days. This is why high power storage favors solar power in the optimal mix of I-RES.

Summary

The results of the correlations, the Greenpeace scenario and the optimization are related. Solar power capacity profiles in Europe are highly correlated between countries. Wind is less correlated, especially between countries with a different latitude. This makes interconnection favor wind power, which is reflected in the share of wind energy in I-RES production in the optimization at +-75% for a copper plate Europe and +-60% with no interconnection. The optimization favors wind power both for a copper plate Europe and Europe without interconnection, because the seasonal profile of wind is better matched to the seasonal demand profile for electricity in Europe. Wind power is mostly installed in Spain, Italy, France and the UK, solar power in France and the UK because the profiles are better matched with the demand profile.

During winter, wind and solar power are uncorrelated. In summer wind has a diurnal profile which makes the problem of high power output during the day worse, especially in Mediterranean countries. This leads to curtailment during summer, both in the Greenpeace scenario and with the optimized installed capacities. Interconnection decreases curtailment of solar power by a factor 8 and of wind power by a factor 17 in the Greenpeace scenario, because wind is less correlated.

The capacity credit of I-RES is strongly affected by interconnection, going from 4.6% of peak demand in the Greenpeace scenario without interconnection, to 12.5% for a copper plate Europe to 23.8% if the installed capacities of the Greenpeace scenario are redistributed over Europe. The forced exchange increases from 0% to 7.5% and 23.8%, respectively. So interconnection increases the capacity credit of intermittent renewables, with decreasing marginal returns. Interconnection increases capacity credit because the capacity credit is defined by the moments in winter when wind power output is low and wind is not fully correlated.

The unconstrained optimizations further increases the capacity credit. In the 3-hour optimized mix I-RES have a capacity credit of 26.1% of peak demand, even with less exchange than the Greenpeace scenario. The seasonal optimal mix has a capacity credit of 43.8% for the copper plate Europe; the large storage volume of 1.4TWh increases the capacity credit. The seasonal optimal mix with no interconnection has a capacity credit of just 8%. This means that storage can increase the capacity credit, but only when countries are interconnected. The storage volume influences the optimal mix, with larger storage favoring solar power until a ratio of 60% wind and 40% solar power is reached in a copper plate Europe when storage capacity is in the order of 5 TWh.

Discussion

It has been shown in this study that it is possible to redistribute capacity in Europe such that I-RES production profiles are far better matched to the demand profile than in the Greenpeace scenario for 2050. A relation between interconnection, storage and the optimal mix of intermittent renewables in Europe was found. However, many assumptions had to be made and there are some uncertainties which need to be discussed. First the uncertainties in the production profiles, then in the model and optimization. Recommendations to decrease uncertainties and reduce errors are also made. Finally, the results are compared with previous research.

Production profiles

Solar

The weather data has a 3-hour time resolution. For solar irradiation, the value given in the ECMWF dataset is the mean over the three hours before, which means that cloudy periods during those three are incorporated in the data. The data given was global horizontal irradiation and to calculate the irradiation on an inclined plane the method by Olmo et al. was used (Olmo, Vida, Foyo, Castro, & Alados, 1999). This method is accurate for high solar angles but for shallow angles the model slightly overestimates the irradiation on a plane because anisotropic ground reflectance is not properly taken into account. This means that production in winter and in the evenings and mornings will be slightly overestimated (+-5%).

There are some errors in the GHI in the weather data. This results in a kWh/kWp value in the Netherlands of 1025, compared with 875 kWh/kWp as the current established value (van Sark, 2014). This is a systematic deviation, which changes the capacity installed but does not change the solar production pattern.

The profiles can be improved in a further study by correcting for the anisotropic ground reflection which is also mentioned in the article by Olmo et al. and by correcting the global horizontal irradiation values.

Wind

For wind power a wind speed-power curve for onshore and for offshore wind was assumed. These curves were based on modern (2010-2015) wind turbines which may not reflect the behaviour of wind turbines a few decades from now, though the basic properties of scaling with the cube of wind speed to a maximum value will most likely be the same. The most uncertain factor is in the wind speed at hub height. The wind data is instantaneous data at 10 meters height in a large grid cell of typically 40 by 40 kilometers, whereas wind power siting is very sensitive to local conditions and requires lots of on-site measurements. Because the average roughness parameter over a large area is taken instead of the best sites within the grid cell the roughness parameter is overestimated. This decreases wind speeds at hub height on land and wind production on land is underestimated.

This is reflected in the analysis done by A.S. Brouwer on this study. He found a systematic overestimation of capacity factors for coastal countries compared to real production data for 2002-2012, which is caused by the use of modern wind speed-power curves and a high estimate for the availability. On land, the mean annual capacity factors were lower than real production data, most likely because of overestimated roughness lengths. However, A.S. Brouwer showed that the overall profile, once corrected for these systematic errors, matches real production data quite well and beats the dataset used for the TradeWind study, which was based on 6-hourly reanalysis data.

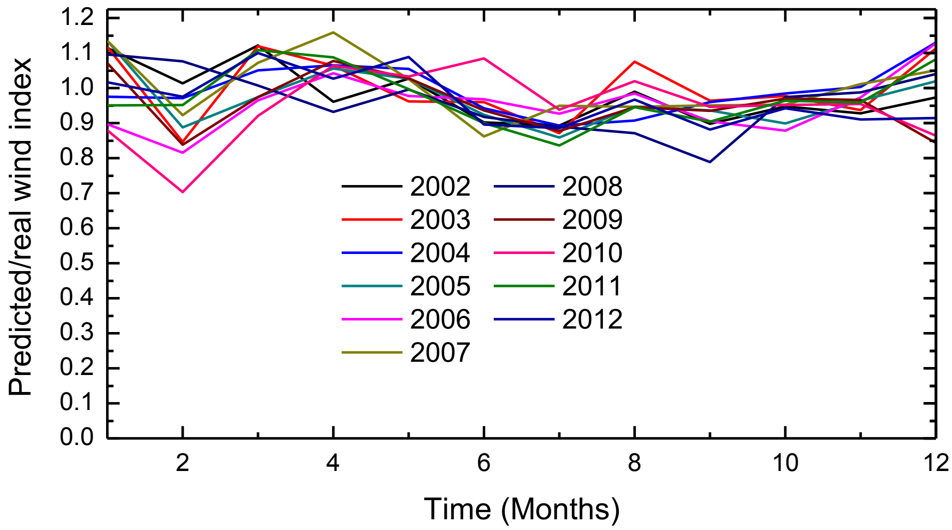

Figure 28: Difference between the wind power outputs predicted in the model and real historic wind indices for Denmark. Both have been normalized with respect to the average output over a year. Deviations are largest in winter, there are no systematic deviations in the profile.

Offshore wind power output has the biggest uncertainty because of the lack of weather data far from the coast. Currently installed wind capacity is situated relatively close to the coast but in the future wind turbines will be placed further offshore. A small correction was made by increasing capacity factors by 10% in the offshore profile when the capacity factor is smaller than 1, but there will be an error in the capacity factor and the installed offshore capacity should be taken as an estimate.

The relation between offshore wind and coastal wind has been treated in the article ‘Models for estimating offshore winds from onshore meteorological measurements’ (Hsu, 1981). It was found that the deviation between offshore and onshore was highest at low wind speeds; the minimum wind speeds are higher offshore than onshore. During winter, offshore wind has a higher capacity factor than onshore because of winter storms. In summer, offshore wind far from the coast does not have the insolation driven diurnal pattern.

This means that the treatment of offshore wind does not just have a systematic error changing the capacity factor but there is an error in the pattern as well. The capacity factor in winter is underestimated and the diurnal pattern during summer is overestimated.

In a further study real offshore wind reanalysis data should be incorporated. If such data is unavailable, a quantitative model which relates coastal wind speeds to offshore wind speeds such as the one described by Hsu should be used to decrease the error. For onshore wind the roughness length used in each grid cell to calculate wind speeds at hub height should be decreased because wind power is installed at the best sites in each grid cell.

Model and optimization

Using the production profiles the Greenpeace scenario was analyzed and the capacity distribution was optimized. In the model of the European electricity system interconnection is not modelled explicitly, which makes it unrealistic, since interconnection is either unlimited or zero. It should be seen as an extreme case but the basic relations found between the key indicators and interconnection in this thesis will apply to more realistic models of interconnection as well. This is because no interconnection and a copper plate are the limiting cases on a continuum going from zero to infinite interconnection. As long as the relation between interconnection and the key indicators does not change suddenly between these points the basic relations found in this study hold.

Demand

The future demand profile was based on the demand profile for recent years, taken from the ENTSO-E database. The annual demand was adjusted to match the annual demand in the Greenpeace scenario. This annual demand is a very rough estimate based on population growth, economic growth and technological change. But the exact increase in demand is not critical to this research, the change in the profile is more important. The seasonal pattern will be influenced most by heating. Some countries, such as France, have very high electricity demand in winter because of electric heating. Should they switch to heat pumps, winter demand will decrease. In countries which use gas for space heating, such as the Netherlands, winter demand will increase if electric heat pumps are used. Because the effect is so uncertain and because the effect is not the same for each country, the seasonal profile was kept the same as in 2010-2012. It is outside of the scope of this research but changes in the seasonal electricity profile can have a big impact on the optimal mix between wind and solar power.

The diurnal profile could also change. The most disruptive technologies in the foreseeable future are the electric vehicle and demand response technologies. Both of these can change the demand profile on shorter timescales. Demand response provides flexibility to the system and therefore should be treated the same as storage and should not be incorporated in the fixed demand profile. The potential of electric vehicles to provide flexibility is still an open question.

The composition of the installed conventional capacity was not considered, but the effect of must-run base load capacity can be taken into account simply by reducing the demand profile by a constant amount.

Storage
A simple storage module has been included in the model. The storage is filled when there is an excess of I-RES and emptied when demand is higher than production from I-RES. Demand response can also be seen as a form of storage, increasing effective demand when production from I-RES is high and decreasing effective demand when there is a shortage of power.
The volumes of the storage were within reasonable bounds, even the 1.4 TWh in the seasonal optimal mix is feasible compared with the potential volumes of storage in Norway (SRU, 2011). However, the storage can fully charge and discharge within a 3-hour time step. For the Greenpeace scenario this results in maximum charge or discharge powers of 100 GW, or about 1/7th of peak demand. In the seasonal optimal scenario this results in peak charge or discharge of +-450 GW. The latter value is extreme. The storage volume is often emptied a few hours after charging during summer with relatively high powers because I-RES production suddenly decreases at nightfall. This means that conventional batteries, flow batteries or electric vehicles could provide some of this flexibility to the grid since these technologies have a relatively low power cost and a high power to capacity ratio (Ekman & Jensen, 2010). During winter periods of over- or undersupply of I-RES last a few days to a week, favoring technologies with a lower price per kWh but with less power, such as compressed air energy storage or even pumped hydro (Hedegaard & Meibom, 2012).
It would be a big improvement to the model to include multiple storage volumes, each with its own capacity/power ratio and investigate the relation between the optimal mix of wind and solar power and both types of storage.

Interconnection
In our model countries are not nodes with constraints on exchange between them; interconnection is not modelled explicitly. Demand and production is either pooled together assuming there is a copper plate or each country is treated separately, assuming no interconnection. While these extremes give insight in the *relation* between key parameters (capacity credit, share of I-RES, curtailment) and interconnection it is not quantitative and there is no insight in diminishing returns. Most likely, the marginal returns of interconnection will decrease as a function of interconnection. With a nodal model the marginal returns of interconnection can be explored for a range of interconnection capacities and the capacity distribution can be optimized for different degrees of grid integration. This would be the first and most important expansion of the model.

Spatial resolution
Optimizing the installed capacities of I-RES per country is a constrained nonlinear optimization problem. The storage module features max functions and absolute value functions, making the problem highly nonlinear and causing discontinuities. This means that linear optimization cannot be used and more computationally expensive techniques need to be used.
One of the aims of the project was to optimize capacity on a grid cell level. Due to the large amount of variables this creates and because the computational time required for the optimization to converge scales with the number of variables squared the optimization was performed on country level instead. Optimizations on a 0.5° by 0.5° grid resolution often failed to converge. As an alternative, a resolution in between could be used so that large countries are at least divided into regions. A spatial resolution of 200 by 200 kilometers would reduce the number of variables by a factor 25 and is a possible solution for the problems with convergence and computational requirements.

Optimization

The constraints for the minimum and maximum values of the capacity in each country were very loose for the 3-hour and seasonal optimizations. For the optimization based on the Greenpeace capacity the constraint was more realistic, but especially for onshore wind in densely populated countries and for offshore wind the maximum capacities are high. High installed capacities are to be expected for an optimization which leads to a penetration level intermittent renewables of 77.9% or higher. The installed capacities are however well within theoretical limits on the maximum densities of wind and solar capacity as described in the article ‘Quantifying a realistic, worldwide wind and solar electricity supply’ (Ecofys, 2015).
The 3-hour and seasonal optimal mix had no further constraints. Putting a constraint on the share of I-RES in production and including an exchange module in the model will already constrain I-RES capacities and yield more realistic installed capacities. The optimal mix of wind and solar power may depend on the penetration of I-RES. If it is possible to run the optimization with a constraint for the share of I-RES, the relation between the share of I-RES and the optimal distribution of I-RES can be investigated. The optimization can then be performed for the entire range between 0% and 100% I-RES penetration.

Because the share of I-RES is calculated from the net renewable production after subtracting curtailed energy it is not linearly related to the installed capacities. Because of the discontinuous nonlinear relation between the share of I-RES and the installed capacities the solver has extreme difficulty in finding a solution to the optimization problem other than the starting point if the share of I-RES is a constraint. The starting point is a local minimum and the nonlinear solver does not find a feasible direction in which the objective function decreases using any algorithm. Nonlinear global optimization with a discontinuous objective function and a discontinuous nonlinear constraint is difficult and a method that uses derivatives like the interior point algorithm is unlikely to find a solution.

This problem could be overcome by using a global solver which generates a host of starting points whose convergence does not depend on derivatives. Particle swarm optimization (PSO) is an example of such a technique. It generates a large amount of starting points and these move through the parameter space with a velocity vector that depends on the best solution in their neighborhood. The standard MatLab particle swarm optimization solver is suited for unconstrained problems (Mathworks, 2015), but constrained particle swarm optimization is possible (Hu & Eberhardt, 2002). Another possible technique is the genetic algorithm; a derivative free method for which nonlinear constraints are supported. Both techniques are computationally expensive but may be a solution to constrain the share of renewables in our optimization.

In the in the objective function curtailment had the same weight as shortages. This may not be a fair treatment of curtailment and perhaps curtailment should be weighed less. This is because at times of extreme oversupply of I-RES energy can be curtailed or dumped in low value applications such as low temperature heating. Curtailment during winter could be used for space heating, curtailment during summer for water heating (Kerkhoven, 2014).

There is never a guarantee that the solutions found were global minima. To improve the probability that the solution found was a global solution global solvers were used in MatLab. Using global solvers the optimization problem is solved using a large number of starting points. For the 3-hour optimization, for the seasonal optimization and for the constrained optimization all starting points yielded the same result. This increases the likelihood that the optimal installed capacities that were found were actual global minima.

Comparison with previous research

Our production profiles based on reanalysis weather data are in good agreement with real production data. This is why the model resulted in the same share of intermittent renewables as the Greenpeace scenario when the capacities of the Greenpeace scenario were used in the model.
The correlations found in wind power production suggest that the most critical connections to balance wind power are the connection between Spain and France, Italy and France/Germany and the UK to continental Europe. This is also a conclusion of the TradeWind study (TradeWind, EWEA, 2009). In the article: 'Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where?' (Schaber, Steinke, & Hamacher, 2012) Schaber concludes the same.

The observation that wind power benefits the most from grid integration in general is also made by Schaber et al. In the article: 'Parametric study of variable renewable energy integration in Europe' they find that the mismatch between I-RES supply and electricity demand in Europe is minimal when the share of intermittent renewables is around 80% and the wind to solar ratio in production is 80% to 20%. This is in good agreement with the results of the 3-hour optimization which gave a share of intermittent renewables of 77.9% and a wind to solar ratio of 74% to 26%.
Without interconnection, they found that the share of I-RES goes to 60% and the wind/solar ratio becomes 60% to 40%. Again, this is in excellent agreement with the results of the 3-hour optimization with no interconnection (62% I-RES penetration, 62%/38% wind to solar ratio). This optimal mix depends on the geographic region studied. For California, the optimal I-RES share is 70%, with a 50%/50% mix between wind and solar power (Hart & Jacobson, 2012).

Heide et al. found a lower share of wind in the seasonal optimal mix than in this study, at 55% and 45% solar (Heide, 2010). This is because their seasonal wind profiles had a higher winter/summer ratio than the profiles in this study. A possible explanation for this is that the optimization distributes wind and solar capacity to different countries with different seasonal profiles than the study by Heide et al. Their optimization places lots of solar capacity in Germany, whereas the optimization in this study places more in France, Spain and Italy.

The capacity credit of intermittent renewables calculated in this study is based on the maximum backup requirement during five weather years. It is determined for the combination of wind and solar energy relative to the peak demand in the system. This is different from other studies, where the capacity credit is often given as a percentage of nameplate capacity and is given for a single type of generation. But since demand is much higher in winter than in summer and the highest peaks occur during the evening, the capacity credit is effectively defined by wind power in this model so results can be compared.

Because the capacity credit is defined by the reduction in backup requirements, the capacity credit can be compared with the need for backup capacity in the studies by Schaber et al. They also found that the need for backup capacity is barely decreased by intermittent renewables if there is no interconnection and that only wind decreases the need for backup capacity (Schaber & Steinke, 2012). They set the required backup capacity for a system with 80% I-RES and a share of wind between 70 and 80% at 70% of peak demand, which is comparable with the figure of 74% (26% capacity credit) in the 3-hour optimized mix in this study.

As a percentage of nameplate wind capacity, the capacity credit of intermittent renewables for the copper plate Greenpeace scenario is 16% in this model. This is comparable with the figure of 14% in the TradeWind study for a highly interconnected European system. The difference in capacity credit between a copper plate Europe and Europe with no interconnection in this model is a factor 2.5, whereas the TradeWind study puts this factor at 2. In the 3-hour optimized mix, with higher installed wind capacities than in the Greenpeace scenario, the capacity credit of wind is 11.6% of nameplate capacity, which means that there are decreasing marginal returns to installing more capacity.

In the article 'Grid versus storage in a 100% renewable Europe' Steinke et al. concluded that high power storage with short charge and discharge times are economically the most feasible and that this favors solar power. This is in agreement with the results of the optimizations for different storage volumes in this study, where it was observed that the share of solar power increases with higher storage volumes. The relation between the capacity credit of I-RES, storage and interconnection is not discussed in this article. In the seasonal optimal mix the capacity credit of intermittent renewables rose dramatically to over 40% with 1.4TWh storage, whereas with no interconnection it was below 10%, even with an enormous storage volume of 3.4TWh. It seems that storage can increase the capacity credit of intermittent renewables only when countries are well interconnected.

Overall, the results are in good agreement with existing literature and new observations have been made. The combined effect of storage and interconnection on the optimal mix of intermittent renewables requires further study. A quantitative study of the entire relation between interconnection, the optimal mix of I-RES and the capacity credit and curtailment of I-RES in Europe would be very useful for European renewable electricity policy and could prove the benefits of an integrated approach for dealing with high shares of intermittent renewables on the European grid.

Conclusion

In this thesis the effect of interconnection and storage on the optimal mix and geographical distribution of I-RES capacity over Europe was researched. Production profiles for I-RES were created based on reanalysis weather data, the profiles were accurate and the model yielded results in good agreement with real production data and the Greenpeace scenario. The optimization improved the capacity credit of I-RES and reduced curtailment. The results of the optimization are in line with previous research (Schaber & Steinke, 2012) (Heide, 2010).

Optimizing the installed capacities in Europe can improve the integration of intermittent renewables on the grid dramatically. It can increase the capacity credit of I-RES to 26.1% of peak demand with an I-RES penetration level of 77.8% for a copper plate Europe with just 0.6 TWh of storage. The total net remainder can be improved from 50% of annual demand in the Greenpeace scenario to 33.9% with 0.6 TWh storage in a copper plate Europe. The optimal distribution has a mix of 76% wind energy and 24% solar energy in annual production in a copper plate Europe. Without interconnection the optimal mix is 62% wind energy to 38% solar energy.

Interconnection increases the capacity credit of I-RES and favors wind energy, storage primarily reduces curtailment and favors solar energy. The optimal ratio between wind and solar energy converges to 60-65% wind and 35-40% solar when the storage capacity is increased beyond 3 TWh. High power storage can decrease the need for backup capacity, but only with interconnection. The improvement of the capacity credit of I-RES through interconnection is increased by storage.

In the Greenpeace scenario, interconnection decreases curtailment from 21% of I-RES production with no interconnection to 1% with a copper plate and the capacity credit of I-RES is increased from 4.6% to 12.5% of peak demand. In all optimization with interconnection I-RES reduce the need for backup capacity by only 7-8%, even with renewable penetrations over 60%. Curtailment is increased without interconnection, especially curtailment of wind power. Because wind is most correlated in the east-west direction, north-south interconnection is preferred, especially between the Iberian Peninsula, Scandinavia and Northwest Europe.

The variability in the net remainder is decreased by storage, but extreme events where the net remainder increases or decreases by more than 100 GW/h will occur in the optimized distribution. The diurnal profiles of wind and solar power are correlated in the summer, especially in Southern Europe.

The integration of high shares of intermittent renewables requires interconnection, storage and flexible backup no matter where I-RES capacity is installed. But optimizing the mix between wind and solar power and the distribution of I-RES capacity over Europe can make the integration of intermittent renewables easier, especially when there is sufficient interconnection. The questions of how much interconnection and storage is required and how interconnection and storage affect the optimal distribution of I-RES capacity in Europe quantitatively merit further research.

Acknowledgements

A large part of this research was carried out at TenneT TSO B.V. which is the Dutch high voltage transmission grid operator. I interned at the long term grid planning department in Arnhem, under supervision of Gert van der Lee. I want to thank TenneT TSO for having me as an intern, the people in the department for their feedback on my work and Gert van der Lee for the many good discussions on the integration of intermittent renewables in the energy system and his feedback on my work. I want to thank Anne-Sjoerd Brouwer, PhD student at Utrecht University, for his review of this study.

Machteld van den Broek, assistant professor at Utrecht University, was my supervisor during the project. I want to thank her for her help and her comments on the draft. She kept the project on track, gave structure to the project and the final report and increased the level of the thesis significantly.

References

4C offshore. (2015, 2 19). *www.4coffshore.com*. Retrieved from http://www.4coffshore.com/offshorewind/

Barthelmie, Grisogono, & Pryor. (1996). Observations and simulations of diurnal cycles of near-surface wind speeds over land and sea. *Journal of Geophysical research*, 21327-21337.

Brouwer, Broek, v. d., & Zappa, T. F. (2015). Least-cost options for integrating intermittent renewables in low-carbon power systems.

Danish Wind Energy Association. (2015, June 04). *DWEA Statistics portal*. Retrieved from http://www.windpower.org/en/knowledge/statistics/the_danish_market.html

Ecofys. (2015). Quantifying a realistic, worldwide wind and solar electricity supply. *Global Environmental Change*, 239-252.

Ekman, & Jensen. (2010). Prospects for large scale electricity storage in Denmark. *Energy Conversion and Management*, 1140-1147.

Energynautics GmbH. (2011). *European Grid Study 2030/2050.* Langen: Energynautics GmbH.

ENTSO-E. (2014). *e-Highway 2050 - Data sets of scenarios for 2050.* Brussels.

EPIA. (2014). *Global Market Outlook for PV.* Brussels: European Photovoltaic Industry Association.

EU WATCH. (2015, January). *EU-WATCH Data for researchers*. Retrieved january 1, 2015, from EU Water and Global Change: http://www.eu-watch.org/data_availability

European Climate Foundation. (2010). *Roadmaps 2050: a practical guide to a prosperous low carbon Europe.* Brussels.

European Commision. (2011). *Energy Roadmap 2050.* Brussels.

European Commision. (2013). *Renewable Energy Progress Report.* Brussels.

European Commision. (2014, January). *Energy Policies*. Retrieved from http://ec.europa.eu/clima/policies/2030/index_en.htm

European Environment Agency. (2015, June). *EEA Corine land cover database*. Retrieved from http://www.eea.europa.eu/publications/COR0-landcover

European Wind Energy Association. (2009). *Developing Europe's power market for the large scale integration of wind power.* Brussels: TradeWind.

Giebel, G. (2007). A variance analysis of the capacity displaced by wind energy in Europe. *Wind Energy*, 69-79.

Greenpeace International. (2010). *Energy [R]evolution.* Greenpeace International&EREC.

Greenpeace International. (2012). *Energy [R]evolution 2012.* Amsterdam: Greenpeace International, EREC.

Greenpeace, EREC. (2010). *Renewables 24/7.* Amsterdam: Greenpeace International.

Hammons, T. (2008). Integrating renewable energy sources into European grids. *Electrical power and energy systems*, 462-475.

Hart, & Jacobson. (2012). The carbon abatement potential of high penetration intermittent renewables. *Energy and Environmental Science*, 6592-6601.

Hedegaard, & Meibom. (2012). Wind power impacts and electricity storage - A time scale perspective. *Renewable energy*, 318-324.

Heide, V. B. (2010). Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. *Renewable Energy*, 2483-2489.

Hsu, A. (1981). Models for estimating offshore winds from onshore meteorological measurements . *Boundary Layer Meteorology*, 341-351.

Hu, & Eberhardt. (2002). Solving nonlinear constrained optimization problems with particle swarm optimization. *Proceedings of the sixth world multiconference on systemics, cybernetics and informatics*, (pp. 203-206). Chicago.

IEC. (2011). *Electrical storage - Whitepaper.* Geneva: International Electrotechnical Commission.

Kerkhoven, J. (2014, September 26). *Energiepodium nieuws.* Retrieved from Energiepodium: http://www.energiepodium.nl/nieuws/item/lokale-opslag-elektriciteit-goedkoop-en-eenvoudig-te-regelen

Lund, H. (2005). Large scale integration of wind power into different energy systems. *Energy*, 2402-2412.

Mathworks. (2015, May 17). *Global Optimization Toolbox Users Guide.* Retrieved from http://nl.mathworks.com/help/releases/R2015a/pdf_doc/gads/gads_tb.pdf

Milligan, & Porter. (2008). Determining the Capacity Value of Wind: An Updated Survey of Methods and Implementation. Oak Ridge: NREL.

Moriarty, & Honnery. (2012). What is the global potential for renewable energy? *Renewable and sustainable energy reviews*, 244-252.

NASA SEDAC. (2015). Retrieved january 3, 2015, from Socioeconomic data and applications center: http://sedac.ciesin.columbia.edu/data/collection/gpw-v3/sets/browse

NREL. (2008). *System Advisor Model CSP Reference Manual.* Denver: NREL.

Olmo, Vida, Foyo, Castro, & Alados. (1999). Prediction of global irradiance on inclined surfaces from horizontal global irradiance. *Energy*, 689-704.

Perez et al. (2009, February). Redefining PV capacity. *Public utilities fortnightly*, pp. 44-48.

Poyry. (2013). *The challenges of intermittency in NW european power markets.* Oxford.

Rugolo, & Aziz. (2012). Electricity storage for intermittent renewable sources. *Energy and Environmental Science*, 7151-7160.

Schaber, & Steinke. (2012). Parametric study of variable renewable energy integration in Europe. *Energy Policy*, 498-508.

Schaber, Steinke, & Hamacher. (2012). Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where? *Energy policy*, 123-135.

Silva, Ribeiro, & Guedes. (2009). *Roughness length classification of corine land cover classes.* Maia: Megajoule.

SRU. (2011). *Pathways towards a 100% renewable electricity system.* Berlin: German advisory council on the environment.

Steinke, Wolfrum, & Hoffman. (2013). Grid vs. storage in a 100% renewable Europe. *Renewable Energy*, 826-832.

TradeWind, EWEA. (2009). *Integrating wind: developing Europe's power market for the large scale integration of wind power.* Brussels.

Trieb. (2009). Global Potential of Concentrating Solar Power . *SolarPaces Conference.* Berlin.

TU Delft. (2015). *TU Delft Enipedia power plant database*. Retrieved 1 5, 2015, from TU Delft Enipedia: http://enipedia.tudelft.nl/wiki/Portal:Power_Plants

Twidell, & Weir. (2005). *Renewable Energy Resources.* London: Routledge.

UK DECC. (2015). *Windpower program download page*. Retrieved february 1, 2015, from Windpower program database: http://www.wind-power-program.com/download.htm

van Sark, W. (2014). *Opbrengst van zonnestroomsystemen in Nederland.* Utrecht: Universiteit Utrecht.