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Capacity Credit of Wind, Wave and Solar Photovoltaic

Final Project Report

<Variable renewable energies and long-term system planning:
The contribution of renewable energy sources to security of supply and system adequacy>

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Executive Summary

Project Background and Scope

The remaining amount of global resources, especially oil, coal and natural gas is setting up the agenda for climate and energy policy in the years ahead. With the rapid growth in world population and social development, especially in the parts of the world that do not have a standard of living as the European, there is a need to development and use of other energy sources such as wind, solar and wave energy.

Not only climate issues are pushing for such a development, but also the fact that Europe is a net fuel importer with 50% coal, 85% oil and 60% gas. This also means that there is a need for renewable energy in order to ensure economic development and security of supply.

In this context, EU energy policies and those of its member states focus on three main objectives: increasing the use of renewable energy, enhancing security of supply and reducing climate impact, with targets of 20% of RES in the total electricity production by 2020, and 27% by 2030. This is also the case of Denmark, which has set ambitious goals in the energy sector, and aims to be independent of fossil fuels in the long run.

Under this scenario, renewable energy will have a prominent role in the production portfolio.

The integration of variable renewable energies in traditional energy systems poses new challenges. Whilst variable renewable energies are not dispatchable and vary by the whim of nature, the electricity system has to maintain the balance of supply and demand at each hour of operation.

Accordingly, the aim of this project is to evaluate the contribution that variable renewable energy generation can have to the security of supply of the Danish electricity system. System planning is the process that assures security of supply and system adequacy; it assures the ability for the system to meet peak demand even under the most extreme condition. As such, system adequacy forecasts evaluate the ability of generation units to operate when most needed by the system. Traditionally, this analysis has been based on the capacity credit parameter, which is calculated on a yearly basis and evaluates the amount of power a generation unit can reliably be expected to produce at the times when demand for electricity is highest.

In Denmark wind power plays an important role to the current electricity system; however, in long-term planning it is assumed that the contribution of wind energy to system reliability is zero. Solar photovoltaic (solar PV) has the potential to become more and more relevant in the Danish system; and generation from wave energy converters can also be expected to happen in future years.

Therefore, there is a need to examine whether new renewable energy forms of production, such as wave power and solar PV, along with wind power, can be included in the planning of future energy systems. This assessment is done in the present project, first from a qualitative point of view and secondly in measurable terms.

The analysis is based on historical hourly data from offshore wind, onshore wind, wave and solar PV power production and is done over a year. Year 2013 is the study year, and Denmark is the reference system of the analysis. Certainly, the datasets of wave and solar PV power production for year 2013 and the hour by hour analysis add unique value to the project. Also, the fact that the analysis takes into account an electricity-only and an integrated energy system, as well as flexible and inflexible electricity demand, contributes to the novelty of the project. Moreover, the analysis goes beyond the wind-dominated system of today, towards a wind-wave-solar PV system based on Denmark's potential, investigating the potential of two very important RES.

Project's Conclusions

Two major conclusions arise from this project. The first one is related to the renewable energy mix that Denmark has chosen for coming years, and the second one relates to the capacity credit of RES.

Denmark has set ambitious goals in the energy sector and by 2035 it aims to be independent of fossil fuels in the heat and electricity sector. In order to achieve 2035 goals, offshore and onshore wind generation are meant to increase significantly, and only small amounts of solar PV and almost none wave power are envisioned in the renewable energy mix. Therefore, Denmark has chosen a wind-dominated renewable energy system for the future.

This study has investigated the benefits of a combined wind-wave-solar PV mix compared to a wind-dominated system, based on the wave and solar PV potential of Denmark, and the clear advantages in combining the three RES together instead of harnessing only one of them. For example, wave energy is less variable than wind energy, waves are more predictable than winds and waves are normally some hours delayed with regards to the winds that have created them –which allow wave energy converters to cover the gaps in production from wind turbines–. Solar PV does not follow the variations of production of wind nor of wave energy, and thus, it can complement the power production of the other two.

Other positive effects among the three RES are the following. The three are seasonal resources that complement each other; wind and waves are stronger in the winter period, when electricity demand is highest, and solar PV production is correlated to daily consumption patterns. Solar PV and, to a large extent, onshore wind can act as decentralised generation, which reduces transmission losses, and the three RES are available locally, regionally or nationally, which increases nations' security of supply. In addition, the following synergies arise when combining offshore wind and wave: they can share part of the supply chain, the electrical and marine infrastructures, skills and offshore O&M facilities.

In particular, the project has explored the relationships among the three renewable energy sources and what they individually and in synergy can provide to the electricity system. For this, the correlation between RE production and demand, the correlation between wind, waves and solar PV, and the number of hours per year of null-, minimum- and full-production of different RE mixes, have been examined.

Results of the project show the following findings:

i) Onshore wind and solar PV are the RES higher correlated to the classical electricity demand, with a cross-correlation factor of 0.14 and 0.13, respectively.

ii) Among the scenarios studied including offshore and onshore wind, the highest cross-correlation factor between RE production and demand is achieved by combining offshore wind, onshore wind, wave and solar PV; and the cross-correlation factor is of 0.17. These numbers can be compared with the cross-correlation factor of RE production and demand in year 2013, of 0.13.

iii) There is high correlation between wind and wave power production, which is explained by the fact that waves are created by winds; cross-correlation factors are between 0.6 and 0.7 for a zero-hour time lag. However, and interesting property is that there is also an average delay between wind and wave production, which lies in between 1 to 2 hours for offshore wind production, and 1 to 4 hours for onshore wind production.

iv) Solar PV is low correlated with offshore wind, onshore wind or wave production, presenting a low negative correlation.

v) Among the scenarios analysed, the renewable energy mix that combines offshore wind, onshore wind, wave and solar PV is the one that reduces to a minimum the number of hours per year with a production below 1% of total production, and the number of hours per year with a production below 5% of total production, with numbers of 190 h/y and 2070 h/y, respectively. The combined offshore and onshore wind energy system presents numbers of 519 h/y and 2786 h/y, respectively.

vi) An interesting finding, which relates to the second set of conclusions to be presented below, is that the number of hours per year with no production from RES is as low as 0 h/y in most of all the RES scenarios analysed including the four RES of the study.

As a result, the first set of findings of the project highlight that there are stronger benefits in a Danish diversified renewable energy mix based on wind, wave and solar PV, than in the wind-dominated renewable energy system that Denmark is aiming for.

The second set of conclusions is related to the capacity credit of RES in the Danish system, and the contribution that RES can provide to security of supply.

In system adequacy assessments the contribution that RES can make to security of supply is evaluated by the capacity credit parameter. However, the traditional general assumption in adequacy forecasts is that variable renewable generation cannot contribute to system adequacy, and thus, that the capacity credit of RES is equal to zero. This project has aimed to go beyond this assumption and has investigated different methods to evaluate the contribution that RES can provide to the Danish system.

Accordingly, the capacity credits of different future 2030 Danish scenarios including offshore wind, onshore wind, wave and solar PV have been examined. Results of the project have proved that RES do have a positive capacity credit, with a value above zero.

Results obtained in the project based on a new approach show that the contribution to security of supply that can be expected from RES averaged over a month in the worst month and in the peak-demand month of the year is in the range of 15% to 30% of RES's installed capacity. The interval 15% to 30% depends on the scenario, as the more offshore wind and wave installed in the system, the higher the capacity credit of the RES mix. The opposite is true for onshore wind and solar PV, being solar PV the RES that presents lower capacity credits.

According to the scenarios analysed, a capacity credit of 15%-30% indicates that in a monthly average between 2000 MW and 3000 MW are available in the worst month (February in this analysis) and in the peak-demand month (January in this analysis) to cover the electricity demand. This finding applies both when considering an electricity-only system and an integrated energy system. And again, the intervals depend on the scenario considered.

If the daily averages are considered instead, the average capacity credit of the RE mix in the worst day of the year (when demand is maximum and RES production is minimum) is of 3%-4% of RES installed capacity. This corresponds to 300MW-400MW, and applies both when considering an electricity-only system and an integrated energy system.

By contrast, the average capacity credit of the RE mix in the peak-demand day of the year (when demand is maximum) changes significantly when considering an electricity-only or an integrated energy system. In the former system, the capacity credit varies in the range 16% to 27% (around 2500 MW), whereas in the latter system it presents a value of 50% to 70% of the RES installed capacity (between 5500 MW and 7000 MW). This shows the positive effects towards integrating RES of integrated energy systems, where the electricity, heating and transport sectors are merged, and of flexible electricity demand.

In addition, the Danish TSO and the Danish Energy Authority project an improvement of wind and wave harnessing technologies, and accordingly, their capacity factors are expected to increase significantly. This is especially true for wave technologies, which in some scenarios are projected to have capacity factors higher than offshore wind. These improvements provide a different scenario as the one analysed in this project, with the result that the aggregated capacity credit of RES will change positively.

Overall, this project has proved that RES can contribute to security of supply in the periods of more risk to the system, i.e. in worst periods and in the peak-demand periods. And as RE technology developments happen, RES will be capable of contributing more to system adequacy.

Recommendations for TSOs

Finally, the conclusions and results of this project aim towards the improvement of existing rules and methods in system planning, and towards the development of integrated energy systems with high penetrations of renewable energies. A set of recommendations have been made, which TSOs shall consider to implement as part of a new methodology to calculate the contribution of variable RES to security of supply.

These recommendations aim to go beyond the traditional approach used in adequacy forecasts to meet security of supply. The methodology traditionally used by TSOs, the ENTSO-E and the IEA to calculate the capacity credit of RES analyses the production of the RE mix of focus during the 10th to 100th highest consumption hours during a year. This approach is not suitable when RES are part of the electricity generation mix.

Accordingly, this project has developed a methodology that looks into the capacity credit of a RES mix in a new way. It investigates the capacity credit of a mix of RES at different time spans (intraday, intraweek, intermonth and seasonally), at key time periods during a year (in worst periods, in peak-demand periods, in high RES periods and in best periods), and considering two very different energy systems (an electricity-only system and an integrated energy system), and demand responses (flexible and inflexible electricity demand).

The following recommendations shall be taken as part of a new methodology:

- Investigate RES production throughout key time periods during a year, and not only during a given number of highest consumption hours of a year. This study has examined RES power production in periods of peak-demand, in periods where RES production is minimum and demand is maximum, in periods where RES production is maximum, and in periods where RES production is maximum and demand is minimum. Each of the four periods analysed present its own challenges, and therefore it is relevant to address all of them from a system perspective. In some periods RES production can only cover one eight of the electricity demand, and in others RES production is twice the electricity demand.

- Also, two very different periods should be distinguished and analysed: *worst periods (*where RES production is minimum and peak demand is maximum*)* and *peak-demand periods (*where peak demand is maximum*)*. Traditional system adequacy analyses investigate RES production in peak-demand hours; however, results from this analysis indicate that *worst periods* are the ones that pose a challenge to the system, rather than *peak-demand periods*. An analysis on *worst periods* is needed in order to study how the whole system can meet security of supply with minimum amounts of RES.

- Examine RES production throughout different time spans taking into account intra-daily and daily average changes in consumption. This is especially important as the pattern of the electricity demand will change in the future, and therefore peak-demand hours will be shifted to hours in the day where demand is low and RES production is high, or viceversa.

- In addition, the time span analysis looking into different intra-day scales (i.e. 1-hour, 3-hour, 6-hour, 12-hour, etc) shows what the challenges with RES production in the different time spans analysed are. These conclusions, which go well beyond the purpose of this study, are of great benefit to the current discussion on the storage capacity and flexibility that is needed in the Danish system.

- Evaluate RES production from an integrated energy system approach, with flexible electricity demand, and not only based on classical and inflexible electricity consumption. As decisions in 20 and 30 years time are happening now, it is important that this decision's processes take into account changes in demand patterns, as well as changes on how the electricity and the other energy sectors (transport, heat and industry) will interact. This is addressed in this study by implementing an electricity-only system (which is based on classical and inflexible electricity demand) and an integrated energy system (where the electricity, heat, transport and industrial sector interact, and electricity demand is flexible). Major fifferences of using one and the other have been shown.

- In today's Danish electricity market there is no capacity market for RES. After the research carried out in this project, the question on whether a positive capacity credit can be related to a capacity payment arises. Can a capacity credit above zero be related to any money scheme for the RES of focus? This would indeed allow companies and individuals who invest in RES to have an energy payment and a capacity payment. If the Danish goal is to be a fossil free nation in 2050, it might not be too early to discuss such a tariff system. The discussion could also address whether capacity payments should be part of long-term system planning or of system operation.

The report that follows this Executive Summary provides a comprehensive overview of the objectives, background, methodology and approach, and results achieved throughout the project.

Report Index

Nomenclature

Symbols

H_{m0}	Significant wave height spectral estimate	[m]
H_s	Significant wave height	[m]
H_{max}	Maximum individual wave height	[m]
μ	Mean	
N	Number of samples	
P_{prod}	Power production	[W]
P_{rated}	Rated power	[W]
R^2	Determination coefficient	
σ	Standard deviation	
T_e	Energy period	[s]
T_p	Peak period	[s]
T_z	Zero-crossing period	[s]
T_{02}	Zero-crossing period spectral estimate	[s]
u_{wind}	Wind speed	[m/s]

Abbreviations

CC	Capacity Credit
$CC_{Offshore\ wind}$	Capacity Credit of offshore wind
$CC_{Onshore\ wind}$	Capacity Credit of onshore wind
CC_{REmix}	Capacity Credit of the Renewable Energy mix
$CC_{Solar\ PV}$	Capacity Credit of solar PV
CC_{Wave}	Capacity Credit of wave
Cf	Capacity factor
CEEP	Critical Excess Electricity Production
DEA	Danish Energy Association (Dansk Energi)
DK	Denmark
EC	European Commission
ENS	Energistyrelsen (Danish Energy Authority)
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EUR	Euro
EWEA	European Wind Energy Association
GBP	Great Britain Pound
HR3	Horns Rev 3
IEA	International Energy Agency
JRC	Joint Research Centre
LCOE	Levelised Cost of Energy
LOLE	Loss-of-Load Events
LOLP	Loss-of-Load Probability

OES	Ocean Energy Systems
O&M	Operation and Maintenance
PP	Power Plant
PTO	Power Take-Off
PV	Solar Photovoltaics
QC	Quality control
RE	Renewable Energies
RES	Renewable Energy Sources
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
UCTE	Union for the Co-ordination of Transmission of Electricity
UK	United Kingdom

Chapter I – Introduction

I.I Project Summary

The aim of this project is to evaluate the contribution that traditional and new variable renewable energy generation can have to security of supply of a given electricity system. Denmark is the reference system of this analysis, and the capacity credit is the parameter of focus. Provided that the capacity credit is defined as the amount of power variable renewables can reliably be expected to produce at the times when demand for electricity is highest, the project calculates the capacity credit of different future 2030 Danish scenarios including wind, wave and solar PV power production. The study is based on historical hourly 2013 data from offshore wind, onshore wind, wave and solar PV power production and is done over a year.

Denmark has set ambitious goals in the energy sector. By 2035, it aims to be independent of fossil fuels in the heat and electricity sector. In order to achieve 2035 goals, wind generation is meant to increase significantly.

Today's Danish electricity system is characterized by no nuclear power, high percentage of wind generation (in the first half of 2015 it produced about 40% of the electricity demand), high percentage of CHP (combined heat and power) plants, and strong interconnections to surrounding countries. The plan for 2035 is having a system with higher penetrations of wind, small amounts of solar PV and no wave energy; stronger international connections; no diesel or coal power plants, and low capacity of gas turbines.

The integration of variable renewable energies in traditional energy systems poses new challenges. Whilst variable renewable energies are not dispatchable and vary by the whim of nature, the electricity system has to maintain the balance of supply and demand at each hour of operation.

System planning has to assure security of supply and system adequacy, i.e. it has to assure the ability for the system to meet peak demand even under the most extreme condition. Traditional long-term system planning and system adequacy analyses elaborated by Energinet.dk (i.e. the Danish TSO or Transmission System Operator) under the recommendations of the ENTSO-E, are carried out based upon the fact that conventional power plants have a positive capacity credit, i.e. can contribute to system's security of supply. On the other hand, the traditional general assumption in adequacy forecasts is that variable renewable generation cannot contribute to system adequacy.

Basically, system adequacy forecasts evaluate the ability of generation units to operate when most needed by the system; this is, in hours of peak demands. Traditionally, this analysis has been based on the capacity credit parameter, which is calculated on a yearly basis and evaluates the amount of power variable renewables can reliably be expected to produce at the times when demand for electricity is highest.

In Denmark wind power plays an important role to the current electricity systems; however, in long-term planning it is assumed that the contribution of wind energy to system reliability is zero. Solar photovoltaic (solar PV) is becoming more and more relevant in the Danish system; and generation from wave energy converters is also expected to happen in future years.

Therefore, there is a need to examine whether new renewable energy forms of production, such as wave power and solar PV, along with wind power, can be included in the planning of future energy systems. This assessment is done in the present project, first from a qualitative point of view and secondly in measurable terms.

The results of this project can ultimately lead towards the improvement of existing rules and methods in system planning that assess the contribution of renewable energy sources, and the development of integrated energy systems with high penetrations of renewables and where the electricity, heating and transport sectors are merged.

The project has been financed by Energinet.dk, under the PSO ForskVE programme and under the Section of Smart Grids. Project partners and external project advisors include Consulting Engineer Julia F. Chozas, Wave Star A/S, the Sustainable Energy Planning Group of the Department of Development and Planning of Aalborg University, the Wave Energy Research Group of the Department of Civil Engineering of Aalborg University, Danfoss Solar Inverters and The Danish Energy Association (Dansk Energi).

I.II Report Structure

The main purpose of this report is to address the methodology, results and conclusions carried out and derived from this project.

The report is divided in eight chapters and ten annexes. Chapters encompass the core of the report, and annexes complement the information provided in the chapters.

The report starts with an introduction to the project (Chapter I), addressing project objectives and scope.

Chapter II reviews the concept of security of supply. The goal of this chapter is to provide background knowledge in order to understand how current electricity systems are planned, and how renewable energies fit in these systems. Denmark is the system focus.

The following chapters (Chapter III to Chapter VI) assess the actual contribution that variable renewable energies can make to security of supply. In order to carry out this analysis Chapter III describes the methodology utilised, Chapter IV the parameters of focus, Chapter V the main results and Chapter VI the conclusions and discussion of results.

Specifically, Chapter III defines the reference system of the study and its main characteristics, the reference year, the renewable energy sources of the study, the Danish electricity grid, hourly distribution data files selected for the study, and a description of the scenarios of the analysis.

Chapter IV focuses on the parameters utilised to derive the results of the study. Two assessments have been chosen, a qualitative and a quantitative assessment. The parameters utilised in both assessments are explained in Chapter IV.

Accordingly, Chapter V presents and discusses the results of the qualitative and quantitative assessments, respectively. Then, Chapter VI elaborates on the conclusions of the project. It includes a summary of the main conclusions achieved throughout the project, a set of recommendations for TSOs and a summary of recommended further work.

Lastly, Chapter VII summarises the dissemination campaign of the project, and Chapter VIII lists the references utilised in the project.

The ten annexes included at the end of the report complement the information provided in the chapters. They are mentioned throughout the report when relevant. Annex I presents a glossary of electricity systems that supplements the information provided in Chapter II; Annexes II, III, IV and V complement the description of the distribution data files of Chapter III; Annex VI outlines complementary definitions of the capacity credit parameter; Annex VII provides a comprehensive overview of the Results; Annexes VIII presents the results of sensitivity analyses carried out for wave and solar PV distribution data in Denmark; and Annexes IX and X present two papers published in two international conference proceedings.

Chapter II – Project Background: Security of Supply and System Planning

II.I Introduction

Traditional system adequacy analyses are carried out based upon the fact that conventional power plants do contribute to system's security of supply, but that variable renewable generation do not contribute to system's security of supply. If the capacity credit of wave and solar PV is not accounted for in the future, new power plants based on fossil fuels will need to be built.

Accordingly, integration of large quantities of variable RES in the Danish energy system requires technical, organizational and planning changes in the electricity system.

The project builds on security of supply, system planning and capacity credit concepts. As the capacity credit is related to firstly, system reliability, security of supply and system adequacy; and secondly, to long-term system planning, this section reviews the concept of security of supply, system planning and capacity credit.

The following questions are addressed in this section:

- What are the traditional and current approaches to assess long-term security of supply?
- Which parameters are relevant in this assessment?
- How security of supply is related to system planning?
- Which timescales appear in system planning?

The purpose of this section is to provide the background and sound framework of discussion for the qualitative and quantitative assessments that are presented in Chapter IV and Chapter V of the report.

Also, "Annex I. Glossary of Electricity Systems" provides definitios of selected terms that appear when describing and analysing electricity markets and energy systems. Annex I is intended to help the reader to get familiarised with the terminology utilised in this Chapter.

II.II System Stability, System Balancing and System Adequacy

According to the International Energy Agency (IEA, 2011), the reliable integration of renewable sources of electricity is perhaps the most disputed and misunderstood factor in sustainable electricity supply. This is partly because integrating renewables is complex, partly because it implies change in the vitally important activity of electricity provision, and partly because some renewable energy technologies do pose additional challenges.

Some renewable energy technologies are dispatchable, and some others vary by the whim of nature. Dispatchable renewables include geothermal, hydropower, bio-energy and concentrating solar power plants (CSP) with sufficient integrated thermal storage. The output of a second group of renewable energy power plants, including wind power, solar PV and wave energy, is variable and less predictable.

The second group of technologies is of interest to the present project.

The challenge of integrating variable renewable energy is often perceived over three timescales:

- In a timescale of seconds or less, the focus is put on system stability, i.e. voltage stability.
- In a timescale of minutes to days, the focus is put on balancing of demand and supply, also referred to as load following.
- In a timescale expanding from months to years, the focus is put on the adequacy of the power system to meet peak demand, i.e. system adequacy.

The underlying objective in all three cases is the same, to maintain the balance of supply and demand for electricity, but it is important to clarify the distinction among the three timescales.

System stability: The voltage and frequency of any given power system fluctuate continuously with variations in demand and supply. The stability part of the balancing challenge relates to maintaining both within acceptable levels. Every power system has a number of specific resources it uses to achieve this, i.e. certain dispatchable generators (e.g. thermal, hydro plants) that the system operator can rely on more or less instantaneously.

Many power systems have grid codes that specify the services to be provided by power plants within the system. Areas with high penetrations of wind power generally apply robust grid codes which may, for example, stipulate that wind power plants must be able to support the system in case of faults that jeopardise voltage stability. This capability (known as fault ride-through) is important in ensuring such power plants contribute to system stability.

System balancing: Balancing services are needed in the system order to perfectly match supply and demand. These services can be supplied by flexible generation, strong interconnections between grids and/or energy storage technologies such as pumped hydro, compressed-air and large-scale batteries.

System adequacy: The adequacy of a power system refers to its ability to meet peak demand, even under the most extreme conditions. In this regard, the system operator is primarily concerned with each power plant's ability to contribute to firm capacity. Each plant is rated according to its ability to operate and provide firm capacity when most needed by the system operator. Capacity credit is a measure of this. It represents the proportion of the rated capacity of a plant that can be dispatched when most needed (with an acceptable level of certainty). As their output fluctuates, variable power plants generally have a much lower capacity credit than dispatchable plant types.

The capacity credit of variable renewable energy sources and how these can contribute to system adequacy is the focus of this study.

II.III Capacity Credit and Capacity Factor

The capacity credit and capacity factor are both capacity related terms that represent different characteristics of power plants, and that appear in two very different timescales. The capacity credit is relevant in system planning (adequacy) whereas the capacity factor derives from the instantaneous operation of a power plant in every hour of operation.

The Capacity Credit (CC) measures the contribution of a power plant to reliably meet demand (NREL, 2015). It is measured either in terms of physical capacity (in MW) or the fraction of the power plant's rated capacity (%). The term also refers to the conventional thermal capacity that a variable generator can replace without compromising system reliability (Gross, et al., 2007). For example, a plant with 150 MW rated power and a capacity value of 50% could reduce the need for conventional capacity by 75 MW. In the study context, it is calculated as the amount of power variable renewable energies can reliably be expected to produce at the times when demand for electricity is highest (OECD/IEAa, 2011) (NREL, 2015).

The Capacity factor (Cf) is a measure of the average production of a generation unit over a period of time with regards to its installed capacity. It is calculated as a percentage, by dividing the total energy produced during a period of time by the amount of energy the plan would have produced if it ran at full output during that time period (NREL, 2015). Overall, the capacity factor is related to the operation of the generation unit. In case of conventional power plants and non-variable RES, the capacity factor is controllable to a large extent. For variable RES the capacity factor is only controllable in one direction, i.e. downwards.

Therefore, the capacity credit is related to the contribution that a generation unit can make to the security of supply and system adequacy of a given system, whereas the capacity factor is related to the operation of a unit as a measurement of its energy performance.

II.IV System Planning and System Operation

Figure 1 shows the structure and time-intervals of electricity systems. In the timeline the different concepts of system operation, operational planning and system planning are described. The diagram represents these concepts and how they are interrelated in time. These parameters are related to the present project and the capacity credit discussion.

When analysing electricity markets and the integration of variable renewable energies, it is important to emphasize the different timescales of system operation, and operational and system planning. Whereas system operation has a timescale of seconds to days and focuses on the hour of operation, operational and system planning focuses on longer timescales. Operational planning covers a timescale of days to years, and system planning a timescale of 5 to 10 years and beyond.

In system planning the parameter of focus is system adequacy, i.e. the ability for the system to meet peak demand even under the most extreme condition. System adequacy is in turn related to the amount of installed capacity the system must have in order to maintain system reliability. Accordingly, long-term capacity planning and system adequacy assessments take place in order to meet long-term system requirements.

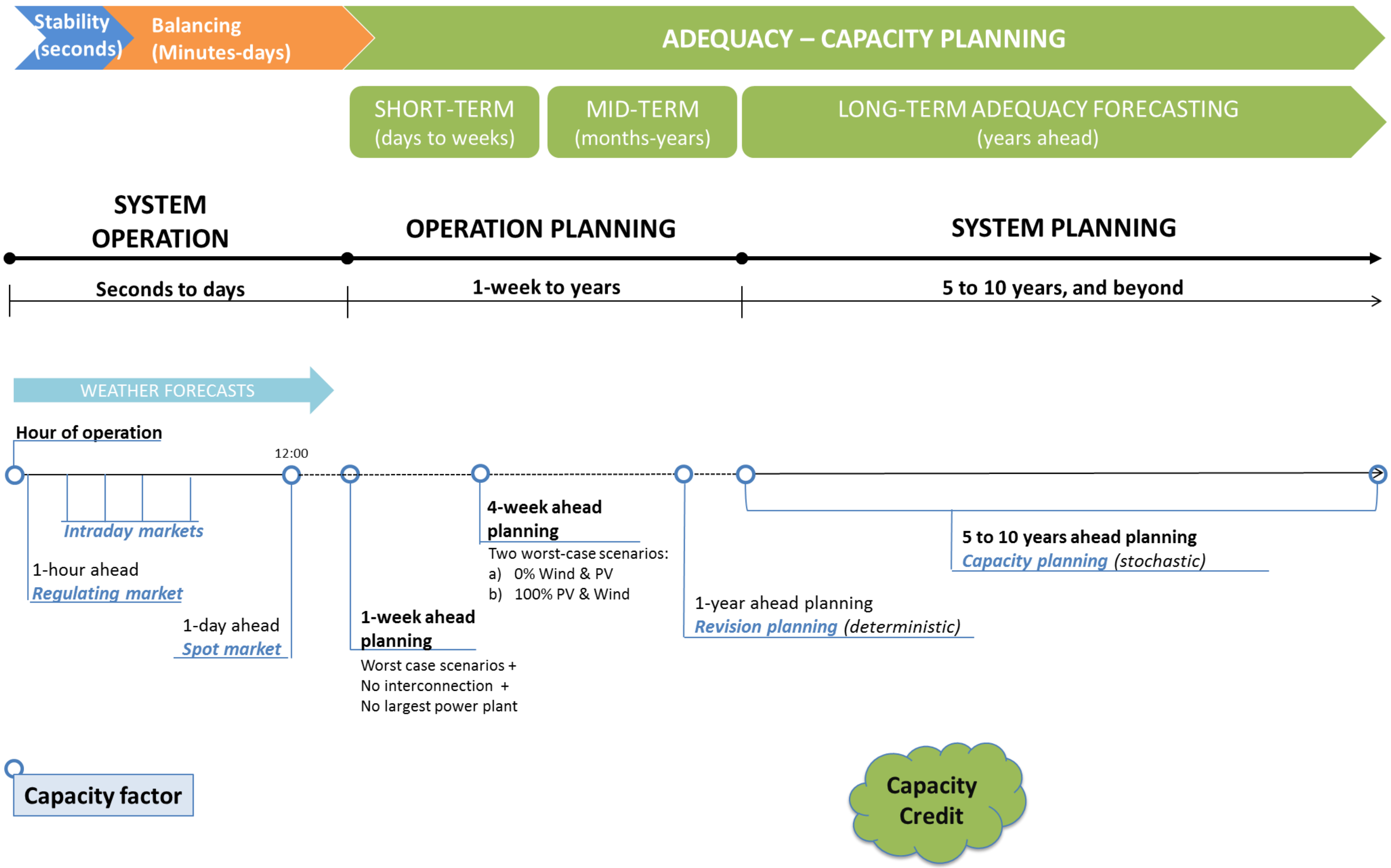


Figure 1. Timeline of electricity markets, the case of Denmark.

II.V System Reliability and Security of Supply

Security of supply, system reliability and system adequacy are three terms referring to the same concept: maintaining a secure and trustable energy system. Any risks on system adequacy will have associated impacts on the security of supply of such system. For example, increasing production, increasing exchanges of electricity and reducing electricity consumption, all contribute to security of supply and to improve system reliability.

Particularly, system reliability refers to two different categories (UKERC, 2006):

a) Maintaining adequate system margin, also known as system adequacy, and
b) Balancing short term fluctuations, i.e. keeping the system in balance.

And accordingly, system operators are responsible of:

a) Ensuring security of supply of a system: they are responsible for maintaining system adequacy at a defined high level. In other words, they should ensure that the generation system is able to cover the peak demand, avoiding loss-of-load events, for a given security of supply.
b) They are also responsible for their area to be electrically stable, i.e. frequency to be kept at 50 Hz.

In consistence with the purpose of this study, system reliability refers to system adequacy and ensuring security of supply of the system.

The various national regulations regarding the level of security of supply range from a 99% security level to 91%. A 99% security level means that in 1 out of 100 years the peak load cannot be covered; this level is applied in Denmark, The Netherlands and Germany. A 91% security level translates into 1 event in 10 years, and is applied in the UK.

II.VI System Adequacy and Adequacy Estimations

System adequacy is the ability of the electricity system to meet electricity demand at all times with an acceptably high probability (OECD/IEAa, 2011). It measures the ability of a power system to cope with its load in all the steady states it may operate in under standard conditions (EWEA, 2009).

This adequacy has different components (EWEA, 2009):

- Generation adequacy assessment: The ability of the generation assets to cover the peak load, taking into account uncertainties in the generation availability and load level; and
- Transmission adequacy assessment: The ability of the transmission system to perform, considering the flexibility provided by interconnection and import and export flows.

Peak demand is therefore a strategic parameter, since it determines the required generating and transmission capacities. As a matter of convention for system design purposes, peak load values at specific points during the year – in January and July – are considered (EWEA, 2009). These are named reference points.

As the whole European system is interconnected, it is logical for national TSOs to harmonise their approaches towards system adequacy. Before the establishment of ENTSO-E this was addressed mainly by the larger systems, such as the UCTE[1], NORDEL[2], ATSOI[3] and UKTSOA[4].

The assessment methods of generation adequacy can be deterministic or probabilistic, or a combination of both. Even from a national point of view, the system adequacy assessment involves transnational issues. This is because at the moment of peak load, it may be necessary to have access to power produced by a neighbouring country, so the transmission system should be able to carry and direct these transnational power flows.

System's adequacy is generally annually reviewed over a period of ten years. Generation adequacy assessments are based on the estimation of 'remaining capacity', which can be interpreted as:

- The capacity needed by the system to cover the difference between the peak load of each country and the load at the regions synchronous reference time ('margin against peak load'); or
- Exceptional demand variation and unplanned outages that TSOs have to cover with additional reserves.

Generation adequacy assessment underscores how each country could satisfy its interior load with the available national capacity. Transmission adequacy assessment then investigates whether the transmission system is large enough to enable the potential imports and exports resulting from various national power balances, thus improving the reliability of the European power system.

In the adequacy estimation, each power plant is assigned a typical capacity credit. This takes into account scheduled and unscheduled outages. There are no plants with a capacity credit of 100%, since there is always the possibility that capacity will not be available when required.

In new energy systems, a substantial fraction of the total generation capacity comes from variable power capacity (most of it being wind). Under this scenario it is important to discuss the extent to which installed variable power capacity statistically contributes to the guaranteed generation capacity at peak load. Results from regional system adequacy forecasts indicate that there is not yet a national TSO standard for the determination of RE's capacity credit (EWEA, 2009), and different methodologies for its calculation are recommended (NREL, 2015) (Gross, et al., 2007) (Stoutenburg, et al., 2010) (Giebel, 2005) (OECD/IEAb, 2011). In the study context, it is calculated as the amount of power variable renewable energies can reliably be expected to produce at the times when demand for electricity is highest (OECD/IEAa, 2011), (NREL, 2015).

[1] The Union for the Co-ordination of Transmission of Electricity (UCTE) coordinated the operation and development of the electricity transmission grid for the Continental European synchronously operated transmission grid.

[2] Nordel was a body for co-operation between the TSOs in Denmark, Finland, Iceland, Norway and Sweden.

[3] The Association of the Transmission System Operators of Ireland (ATSOI) was established in June 1999 for the coordinated activities between EirGrid and System Operator Norther Ireland (SONI).

[4] The United Kingdom Transmission System Operators Association (UKTSOA) was established for coordinated activities between the TSOs of the United Kingdom.

The following subsection addresses the methodology proposed by the European Network of Transmission System Operators for Electricity (ENTSO-E) to estimate system's adequacy. ENTSO-E's methodlogy for calculating system adequacy can be considered the historical or traditional method of assessing system adequacy. It uses a deterministic approach and analyses the worst-case scenario. This scenario considers RES production equal to zero.

System adequacy analyses elaborated by the Danish TSO are carried out under the recommendations of the ENTSO-E and follow the traditional approach. In addition to this, Energinet.dk also investigates long-term system adequacy with a stochastic method, based on the LOLP of the system (Energinet.dk, 2014).

II.VI.I ENTSO-E Adequacy Estimations

Previous to the creation of the European Network of Transmission System Operators for Electricity (ENTSO-E), each region issued yearly adequacy forecasts analysis. For example, the UCTE issued annually the System Adequacy Forecast (SAF), where it assessed the Adequacy Reference Margin (ARM) of the system, hence investigating system reliability.

Currently, ENTSO-E delivers the *Scenario Outlook and Adequacy Forecast* reports or SOAF, which have the same goal as UCTE's SAF reports. These reports include a mid to long-term assessment of system and generation adequacy for all ENTSO-E members, for regions and for individual countries. The publication has three objectives:

- To detail at an early stage the scenarios (generation and load evolution) that will form the foundation of the market and network analyses in the ENTSO-E Ten-Year Network Development Plan (TYNDP).
- To assess the generation adequacy of each countries for the studied period by providing an overview of the generation adequacy analysis for ENTSO-E as a whole and for each of the six regional groups defined by the ENTSO-E System Development Committee.
- To describe the generation adequacy assessment for each individual country based on national comments received from member TSOs.

Adequacy analysis (ENTSO-E, 2010):

The adequacy analysis is based on the comparison between the reliably available generation and load at two given reference points in time in the year (the third Wednesday in January at 7 p.m. and the third Wednesday in July at 11 a.m.) over the monitored time period under standard conditions.

The power adequacy analysis is based on a comparison between the available generation capacity and the load, as illustrated in Figure 2, where ENTSO-E (2010) defines the parameters for the assessment as follows:

- Net Generation Capacity (NGC) = Available Capacity + Unavailable Capacity
- Unavailable Capacity: part of the NGC that is not reliably available to power plant operators owing to the limitations of the output power of power plants. It consists of Non-Usable Capacity (resulting from the variability of the primary sources like wind, hydro or solar sources), Maintenance and Overhauls, Outages and System Services Reserve.

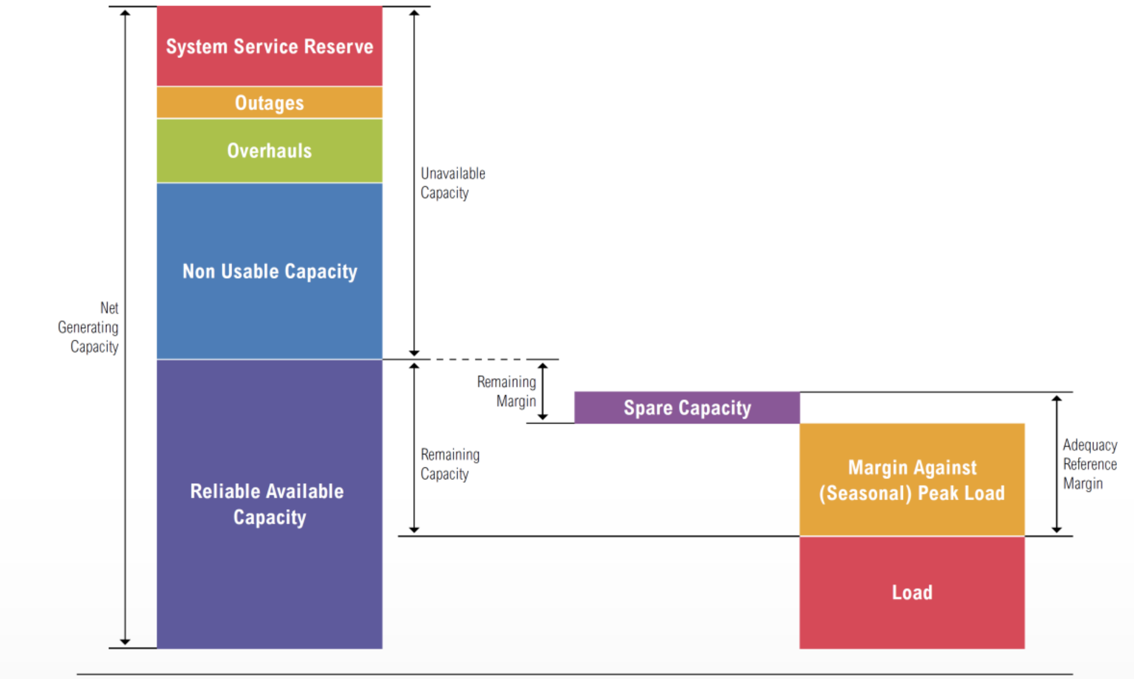


Figure 2. Graphic representation of the power adequacy analysis of ENTSO-E (ENTSO-E, 2010).

- Reliable Available Capacity is difference between the Net generation capacity and the Unavailable Capacity.

- Remaining Capacity is defined as the difference between Reliable Available Capacity and Load (i.e. RC = RAC - load)

Generation adequacy forecast under normal conditions on a power system is assessed at the reference points with the Remaining Capacity value.

- When Remaining Capacity is positive, it means that some spare generating capacity is likely to be available on the power system under normal conditions.

- When Remaining Capacity is negative, it means that the power system is likely to be short of generating capacity under normal conditions.

Seasonal generation adequacy forecast in most of situations is assessed through the seasonal extension of the generation adequacy forecast on a power system, by comparison of the related Remaining Capacity and Adequacy Reference Margin.

- When Remaining Capacity is over or equal to Adequacy Reference Margin, it means that some generating capacity is likely to be available for export on the power system.

- When Remaining Capacity is lower than Adequacy Reference Margin, it means that the power system is likely to have to rely on import flows when facing severe conditions.

Chapter III – Methodology

This section presents the systems and main elements behind the project. It presents the reference system, i.e. Denmark, its electricity portfolio and main characteristics, the reference year, the renewable energy sources of the study, the Danish electricity grid, hourly distribution data files selected for the study, and a description of the scenarios of the analysis.

III.I Reference System: Denmark

Denmark is the reference system for the analyses. It counts with a population of about 5.67 million people (estimates from July 2015).

The Danish primary energy supply has been kept constant throughtout the years at a value of approx. 800 PJ. About 20% of this primary energy supply covers the electricity sector, 30% the heat sector, 20% the industrial sector and 30% the transport sector.

The Danish electricity system is characterized by high percentages of combined heat and power production (CHP), high percentages of wind production, no nuclear power (which indeed adds flexibility in base-load generation) and strong interconnections to neighboring systems.

Figure 3 and Figure 4 illustrate the current Danish electricity system (Energinet.dk, 2015). Three of the exiting offshore wind farms are presented as well as the interconnections to neighbouring countries.

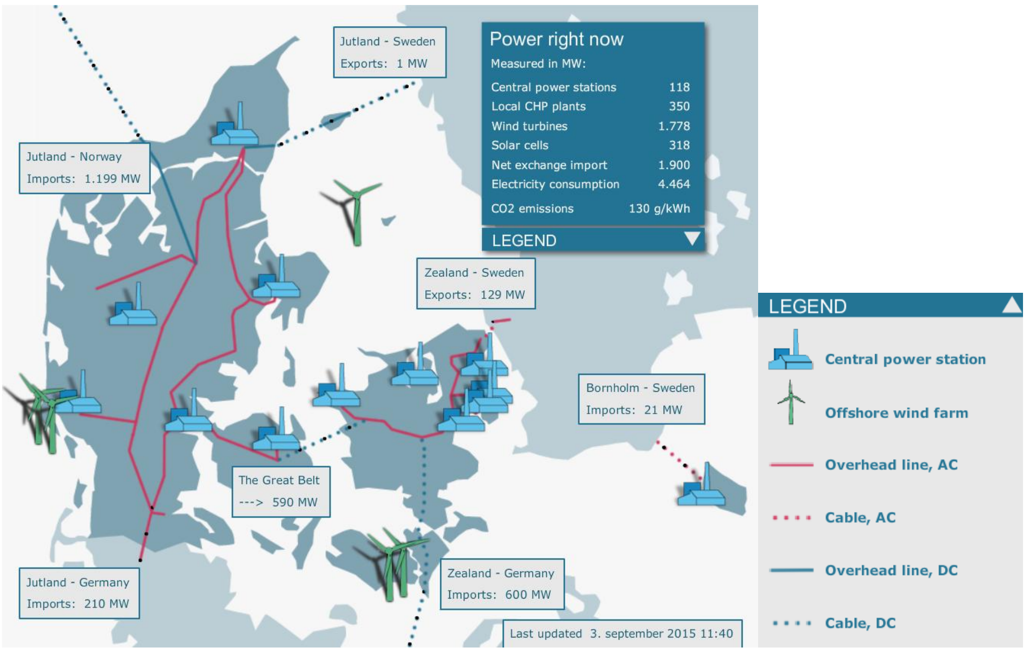


Figure 3. Transmission system and Danish power consumption and distribution on Septmeber 3rd, 2015 at noon (Energinet.dk, 2015).

The role of wind energy in the Danish electricity system has been more and more important along time. In 2010, wind covered in average 21% of the total Danish electricity consumption. In 2014, 50% of the electricity of West Denmark came from wind power, and in year 2015 it is expected that wind covers in average 50% of the total Danish electricity consumption.

In order to illustrate the role of wind energy in the Danish system the figure below shows the Danish electricity system on July 9th, 2015, around 9:30. 90% of the total electricity consumption (4112 MW) was produced by RES, mostly by wind power (3954 MW) and a small amount by solar PV (119 MW).

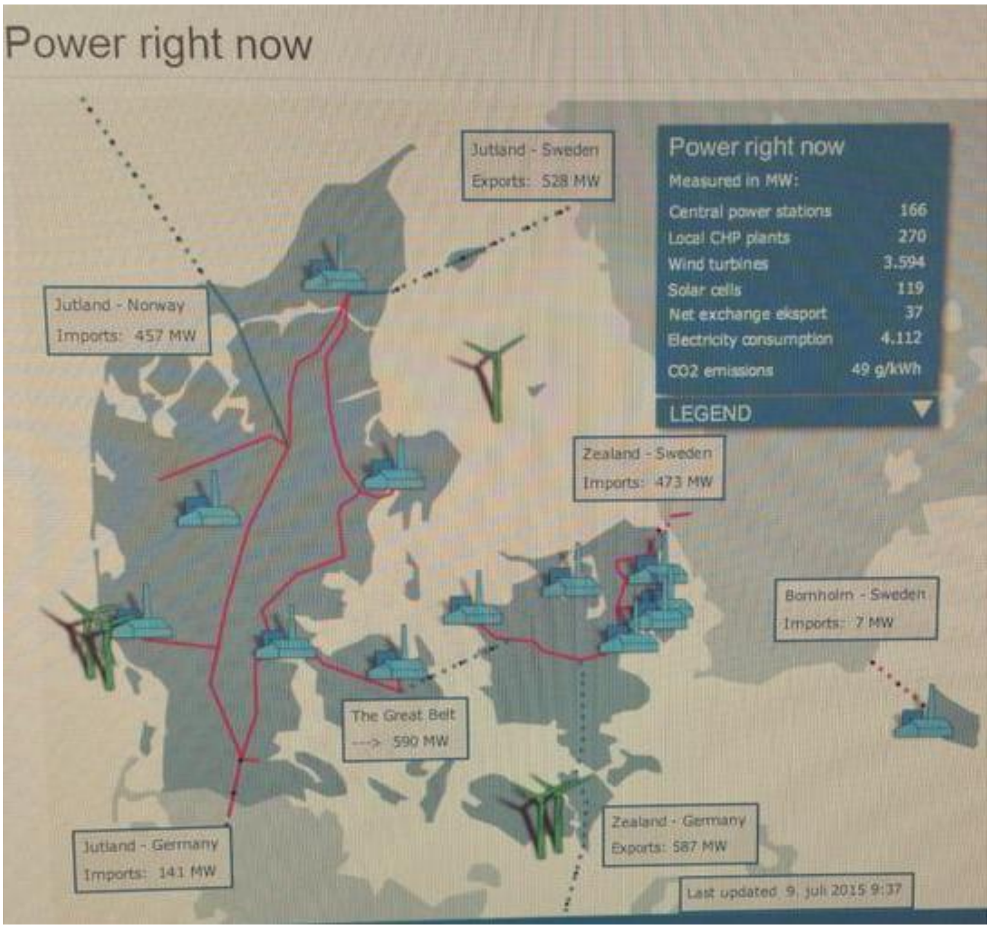


Figure 4. The Danish electric power system on 9th July, 2015, around 9:30 (Energinet.dk, 2015).

III.I.I Danish Energy Targets

Denmark has ambitious energy targets with regards to energy and climate change. It has set up the following targets for years 2020, 2035 and 2050:

Targets for year 2020: 36% of all energy consumption in the electricity, heat and transport sectors covered by renewable energies in 2020; 50% renewable energy production in the electricity sector, 70% of Danish households to receive district heating, 20% reduction of CO2 emissions and 20% energy efficiency.

Targets for year 2035: electricity and heat sectors covered by renewable energies, and thus phase out of coal power plants and of oil-fired boilers.

Targets for year 2050: all energy consumption in the electricity, heat and transport sectors covered by renewable energies.

III.II Reference Year

Reference year is year 2013. Characteristics of year 2013 are shown below:

- February has 28 days
  - Change of time on March 31st and October 27th
- Total number of hours in the year: 8760
- Total number of half-hours in the year: 17520

In order to extrapolate the results obtained from the project's reference year (year 2013) to future years, it is necessary to investigate whether the three RES of the study in year 2013 have been higher, lower or average compared to the average pattern. This is addressed in the following section.

III.III Renewable Energy Sources (RES)

III.III.I Introduction

The present project evaluates the contribution that renewable energy sources can have to the Danish electricity and energy system. The three RES of the study are wind (including offshore and onshore wind), wave and solar PV.

Today's Danish electricity system counts with high amounts of wind power, small amounts of solar PV and none wave capacity. This study investigates what can be the contribution of wave and solar PV to a wind-dominated system, since there are clear advantages in combining the three RES together instead of harnessing only one of them. For example, wave energy is less variable than wind energy, waves are more predictable than winds and waves are normally some hours delayed with regards to the winds that have created them – which allow wave energy converters to cover the gaps in production from wind turbines–. Solar PV does not follow the variations of production of wind nor of wave energy, and thus, it can complement the power production of the other two.

Other positive effects among the three RES are the following: the three are seasonal resources that complement each other. Wind and waves are stronger in the winter period, when electricity demand is highest, and solar PV production is correlated to daily consumption patterns. Solar PV and, to a large extent, also onshore wind can act as decentralised generation, which reduces transmission losses, and the three RES are available locally, regionally or nationally, which increases nations' security of supply. In addition, looking into offshore wind and wave together the following synergies arise: they can share part of the supply chain, the electrical and marine infrastructures, skills and offshore operation and maintenance (O&M) facilities.

Nevertheless, there are still some challenges and limitations ahead large-scale installation of wind, wave and solar PV: economically they are still perceived as expensive and they are, although at different scales, capital intensive technologies; sometimes social acceptance can become an issue; new technologies are perceived as risky and non-reliable for the system; and changes to electricity market's schemes and regulations might be required.

This section of the report reviews the variability and the predictability of each RES, their main characteristics, and Danish projection of their future development. All of the topics addressed here are important to the understanding of the current stage of RES in Denmark and the way towards integrating RES in the Danish grid and creating a diversified RE mix.

III.III.II Offshore and Onshore wind

Variability of Wind

The wind index is a factor (in percentage or per unit) that indicates the wind relative to a normal year, where a normal year is represented by 100% (if the wind index is given as a percentage) or 1 (if the wind index is given per unit). The Danish wind index is determined from actual wind turbine power production of wind turbines all over Denmark, and it has been calculated since year 1979 (Nielsen, 2015).

The figure below presents wind variation from year 1979 to year 2012 (Nielsen, 2015), where it can be seen that wind production in Denmark varies from a minimum yearly production of 80% to a maximum yearly production of 120%, with regards to an average value of 100%.

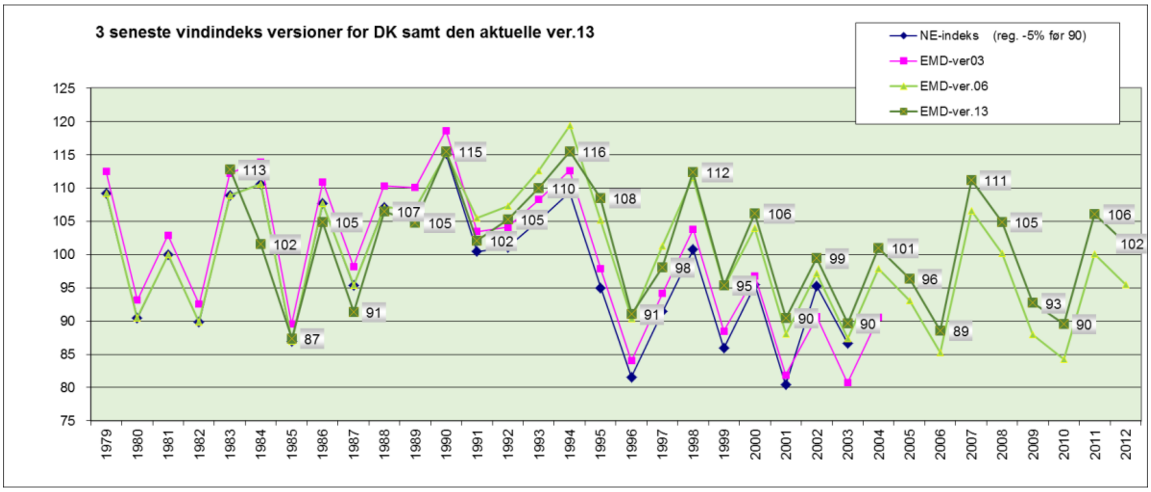


Figure 5. Wind index from year 1979 to 2012 (Nielsen, 2015).

Reference year of the present study is year 2013. According to (Nielsen, 2015) wind index of year 2013 for onshore wind in Denmark was 0.93, and for offshore wind 0.95. This means that the average Danish wind power production in year 2013 was below average, what allow this study to draw conservative conclusions when using wind data of year 2013.

Projections for Wind

Projections for onshore wind capacity factors are shown below according to the Technology Catalogue published by the Danish Energy Authority (Energistyrelsen, 2012):

Technology	**Large wind turbines on land (year of investments decision)**					
	2015	2020	2030	2050	Note	Ref.
Generating capacity for one turbine (MW)	3	3.5	3.5	3.5		1
Rotor diameter (m)	105 – 125	120 – 140	120 – 140	120 – 140		1
Hub height (m)	90	90	90	90		1
Average annual plant capacity factor (%)	34	35	36.5	37	A	1

A: The capacity factors can vary widely depending on the location, as well as the technological characteristics of an individual turbine.

Projections for offshore wind capacity factors are shown below according to the Technology Catalogue published by the Danish Energy Authority (Energistyrelsen, 2012):

Technology	Large wind turbines offshore (year of investment decision)					
	2015	2020	2030	2050	Note	Reference
Average generating capacity per turbine (MW)	4 – 6	6 – 10	10–16	10-20		9 + 11 +14 + 15
Rotor diameter (m)	110 – 155	155 – 180	180 – 200	180 – 250		9 + 11 + 14 + 15
Hub height (m)	80 -100	95 -115	115 -125	115 -155		9 + 14
Annual average plant capacity factor (%)	46-48	48-50	50-52	51-53	A	9 + 15 + 16

A: The capacity factors can vary widely depending on the location, as well as the technological characteristics of an individual turbine. The values hereby stated should be regarded as average.

For year 2050, Energinet.dk estimates the following numbers (Energinet.dk, 2011):

Table 1. Expected wind installed capacity and production in year 2050 (Energinet.dk, 2011).

DK		Max prod (MW)	Prod (GWh/y)	Prod (TWh/y)	Full-load hours (h/y)	Cf (%)
2	Kriegers Flak	1200	4278	4.3	3565	41%
2	Middelgrunden	200	507	0.5	2535	29%
2	Rødsand	366	1414	1.4	3863	44%
2	Onshore wind	800	1607	1.6	2009	23%
1	Anholt	400	1593	1.6	3983	45%
1	Horns Rev (HR)	2260	9771	9.8	4323	49%
1	Læs	1900	7566	7.6	3982	45%
1	Onshore wind	3200	8087	8.1	2527	29%
1	Wind in deep waters (i.e HR)	6750	24741	24.7	3665	42%

- Cf offshore wind: 41%-49% (but for Middelgrunden, which has Cf=29%)
- Cf onshore wind: 23%-29%

Table 2. Wind summary table according to Energinet.dk 2050 projections (Energinet.dk, 2011).

	Max prod (MW)	Max prod (GW)	Prod (GWh/y)	Prod (TWh/y)	Full-load hours (h/y)	Cf (%)
Total Wind	17076	17.1	59564	59.6	3488	40%
Total Offshore Wind	13076	13.1	49870	49.9	3814	44%
Total Onshore Wind	4000	4.0	9694	9.7	2424	28%

Information about the characteristics of the Danish wind resource, relevant wind technologies and the development status of wind in Denmark up to present time can be found in the wind dedicated chapter of the report "Technology Data for Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion" of the Danish Energy Authority (Energistyrelsen, 2012).

III.III.III Wave

Variability of Wave

There are interesting opportunities for wave energy development in the Danish North Sea, in spite of the fact that it has been mostly considered for wind generation. Kofoed (2009) has assesses that wave energy from the Danish part of the North Sea could provide 15% of Danish electricity demand.

Figure 6. Denmark within the North Sea.

The wave climate in the Danish part of the North Sea has been extensively analysed by Ramboll (Ramboll, 1999). The study investigates wave variability and waves characteristics in eight different locations of the Danish North Sea. Figure 7 shows six of the eight points of the study, which are marked with numbers from 1 to 6, as well as Ekofisk and Fjaltring, the two other study points.

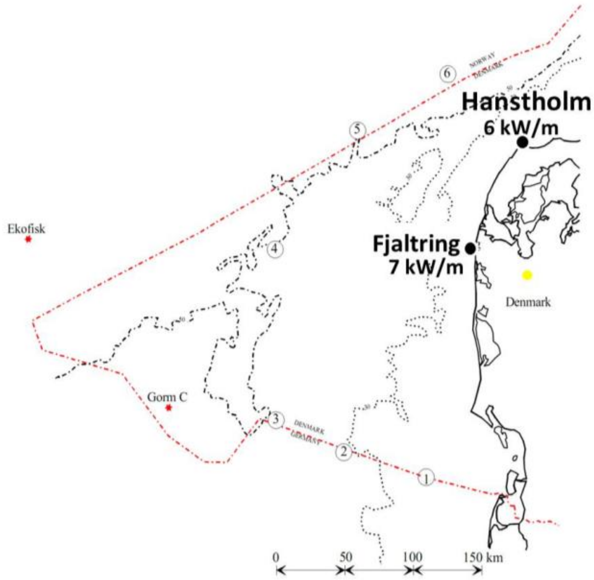


Figure 7. Map of the Danish North Sea. The red dashed line indicate the Danish Exclusive Economic Zone. The eight study locations of Ramboll are indicated by numbers (Ramboll, 1999). Hanstholm and Fjaltring mean wave power and locations are also indicated.

From a wave energy deploying perspective, the two Danish sites that have reached most of the attention have been Nissum Bredning, at the western part of the Linfjord, and Hanstholm, at the

North-West tip of Jutland. It is generally expected that the first wave energy deployments will happen close to shore, in similar waters to those found at Hanstholm. Indeed, the water depth, waves' characteristics and wave patterns of interesting sites such as Hanstholm, Fjaltring and Horns Rev can be considered quite similar.

Due to this fact, this section presents the results of (Ramboll, 1999) for Fjaltring location.

Figure 8 and Figure 9 show the annual and the monthly variability of wave power (in W/m) at Fjaltring. Figure 8 illustrates the variation in mean wave power throughout fourteen years, from 1979 to 1993. Mean wave power is 7 kW/m, the minimum value recorded in the period is 5 kW/m and the maximum value 10 kW/m. This shows an annual variability of up to 40% from the mean annual value.

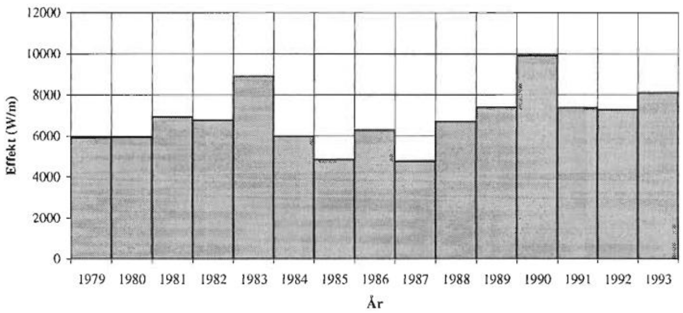


Figure 8. Variation in mean wave power (in W/m) in the period 1979-1993 at Fjaltring (Ramboll, 1999).

Figure 9 presents monthly average values of wave power. Maximum wave power is reached in January, with mean value of 14 kW/m, and the minimum value is recorded in May, of 3 kW/m. November, December and January are the most energetic months, and from April to August the less energetic. This very same pattern can be found in the Danish electricity consumption; where winter period has the highest consumption, and summer period the lowest.

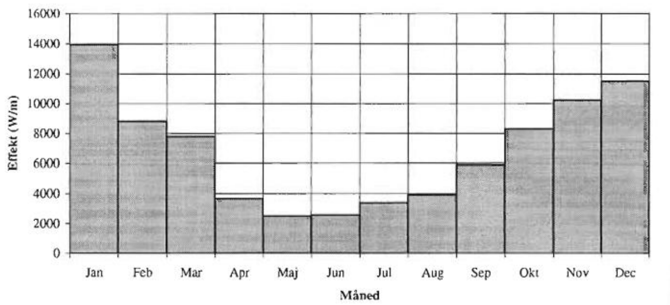


Figure 9. Monthly variation in wave power (in W/m) at Fjaltring (Ramboll, 1999).

Variability of waves and winds

As explained at the beginning of this section, one of the advantages of including wave energy in a wind-dominated RE system is the fact that waves are less variable than winds. And this property can have a positive effect with regards to the integration of RES into the grid.

This subsection compares the variability of waves and winds based on a study carried out at Hanstholm (Fernández-Chozas, et al., 2013). The analysis compared the half-hour variability of waves and of winds based on measured data from two near locations. With regards to wave energy the variability of key wave parameters is presented for H_{m0} (the significant wave height), T_{02} (the zero-cross period), H_{max} (the maximum wave height) and P_{wave} (wave power). With regards to wind energy the variability of key wind parameters is presented for u_{wind} (mean wind speed), MWD_{wind} (mean wind direction) and P_{wind} (wind power).

The parameter *σ/Mean* (standard deviation divided by the mean value) serves as a comparative parameter. Results from the table below show low variability for T_{02} (16%), 46% variability for H_{m0} and u_{wind}, and high variability for P_{wave} and P_{wind} (122% and 136%, respectively).

Generally, P_{wind} varies more than P_{wave}, and u_{wind} more than T_{02} and H_{m0} combined; which are the two parameters in wave energy that dictate wave power production.

Table 3. Half-hour Variability of H_{m0}, H_{max}, T_{02}, P_{wave} and u_{wind}, MWD_{wind} and P_{wind}, at Hanstholm from 26/10/2010 to 09/02/2011.

	Mean	Max	σ	σ/Mean	N
H_{m0} (m)	1.4	4.7	0.7	46%	4157
H_{max} (m)	2.4	8.5	1.1	48%	4157
T_{02} (s)	4.7	8.8	0.8	16%	4157
P_{wave} (kW/m)	8.9	99	10.9	122%	4157
u_{wind} (m/s)	7.7	21.5	3.5	46%	6386
MWD_{wind}	171	357	91	53%	6386
P_{wind} (W/m^2)	472	6141	641	136%	6386

Normally, the diurnal variability of wind and wave power are quite different, with wind power typically showing some evidence of morning and evening peaks. Wave power tends to be quasi-independent of the time of day, and thus adding wave generation to a site could provide more constant production.

Projections for Wave

Projections for wave capacity factors are shown below according to the Technology Catalogue published by the Danish Energy Authority (Energistyrelsen, 2012):

	Wave Power					
	2015	2020	2030	2050	Note	Ref
Energy/technical data						
Generating capacity for one power plant (MW)	1.0 - 30	2.0 - 50	10 - 100	50 - 500		1;1;4;4
Length of installation of one power plant km	0.2 - 2	0.2 - 5.0	1 - 20	5 - 100		1;1;4;4
Annual generated electricity production (MWh/MW)	1500	2500	3500	4500		4

These correspond to capacity factors for wave energy of 17% in year 2015, 28% in year 2020, 40% in year 2030 and 51% in year 2050.

For year 2050, Energinet.dk estimates the following numbers (Energinet.dk, "Energi 2050 – Vindsporet", 2011):

DK		Max prod (MW)	**Prod (GWh/y)**	**Prod (TWh/y)**	Driftstimer (h/y)	Cf (%)
1	Wave	986	5579	5,6	5658	65%

In addition, the document developed by the Danish Partnership on Wave Energy sets a goal for the capacity factors of wave energy in Denmark for year 2030-2035 of 30%-40% (Nielsen, et al., 2012).

Further information about the characteristics of the wave resource, relevant technologies and the development status of wave energy in Denmark can be found at (Energistyrelsen, 2012).

III.III.IV Solar PV

General notes on solar PV in Denmark

The yearly average solar irradiance over Denmark taking into account the cloud coverage is 100 W/m2, and the number of full-load hours is about 970 h/y. The total resource potential of PV in Northwest Europe (including Denmark) is about 1000 kWh/m^2/y. This can be calculated as 115 W/m^2 * 8765 h/y = 1000 kWh/y/m^2.

In spite of the fact that a temperature gradient of 1°C less results for a PV panel in producing 0.5% more, and that in West Denmark wind power refrigerates the units more than in East Denmark; as a general approximation it is valid to assume the same solar PV production in West and in East Denmark.

The boom of solar PV in Denmark happened in years 2012-2013. Solar PV capacity installed by end of year 2013 was 563.4 MW, and by end of 2014, 599 MW.

Variability of Solar PV

The number of production hours of solar PV panels is higher than the number of sunshine hours. This is due to the fact that solar PV panels can also produce in cloud days. However, investigating the variability of sunshine hours allows investigating the variability of solar PV production among years.

The present project is based on measured year 2013 data of solar PV power production. In order to understand whether these data is representative for future years, it is interesting to compare the number of sunny hours in year 2013 to the average value.

As a result, in order to analyse annual solar PV variability the number of sunny hours per year is investigated here. Data has been extracted from DMI, the Danish Meteorological Institute (DMI, 2015). The sum of sunshine hours over a year for Denmark since year 2001 to year 2014 is shown in Figure 10 (DMI, 2014). In this period (year 2001-2014) the average number of sunshine hours for Denmark is 1732 h/y. A significant upward trend in Denmark can be seen.

2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
1564	1691	1869	1724	1846	1703	1709	1821	1793	1669	1683	1674	1780	1727

Figure 10. Sum of sunshine hours over a year for Denmark since year 2001 to year 2014 (DMI, Vejret i Danmark året 2014, 2014).

Annual average sunshine hours for Denmark are 1495 hours, but it varies greatly from year to year and from region to region. For example, in the Kattegat region and the island of Bornholm shining hours are usually between 1600 and 1650 hours per year, and around 1350 hours in the interior of Jutland. Nationally, sunniest year was 1947 with 1878 hours and the most sun-poor year was 1987, with 1287 hours.

Figure 11 shows yearly average of Denmark's sunshine hours since year 1920 up to present. The values are calculated as a national average on the basis of a number of selected stations. (In 2002, DMI converted to a new, automatic and more accurate measurement method; however, this also means that new and old hours of sunshine hours cannot be directly compared. All values on the graph are adjusted so that they are comparable to the new level).

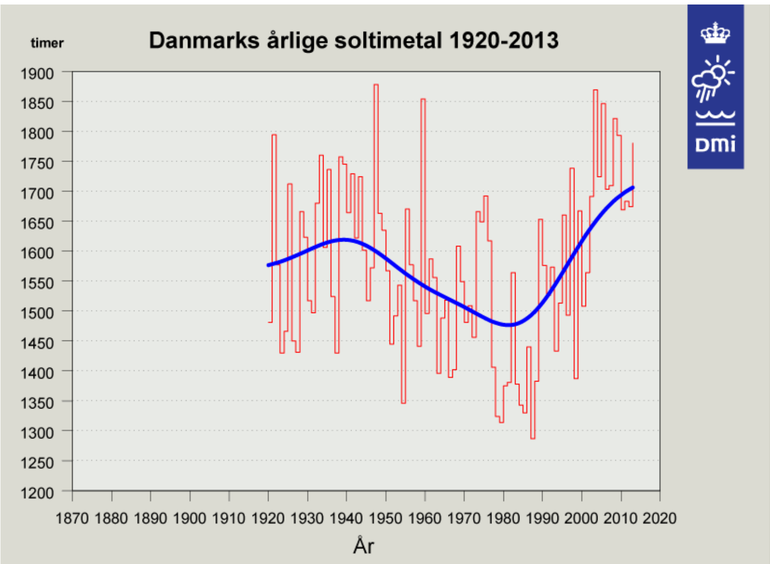


Figure 11. Yearly average of Denmark's sunshine hours since year 1920 up to present (DMI, 2014).

Figure 12 shows the number of sunshine hours in Denmark in year 2013 (DMI, 2013). The sunniest place was the region Bornholm with 1950 hours of sunshine. The region of South Jutland (Syd- og Sønderjylland) had the least number of sunshine hours, 1642.

Overall, the annual average sunshine hours for Denmark are 1495 hours. However, this number has been increasing since 1980, up to a value of 1869 h/y in year 2003. Year 2013 had 1780 sunshine hours. Although this is a much higher value than the annual average for Denmark, it is only a bit above the average value of sunshine hours for the period 2001-2014 (both years included), which has an average number of sunshine hours of 1732 h/y. Based on these average numbers it can be concluded that year 2013 has been a bit higher than an average year for solar PV. This will be taken into account when extrapolating data to future years and in the discussion of results.

Further information about the characteristics of the solar resource in Denmark, relevant technologies in solar photovoltaic and the development status of soalr PV in Denmark can be found in (Energistyrelsen, 2012).

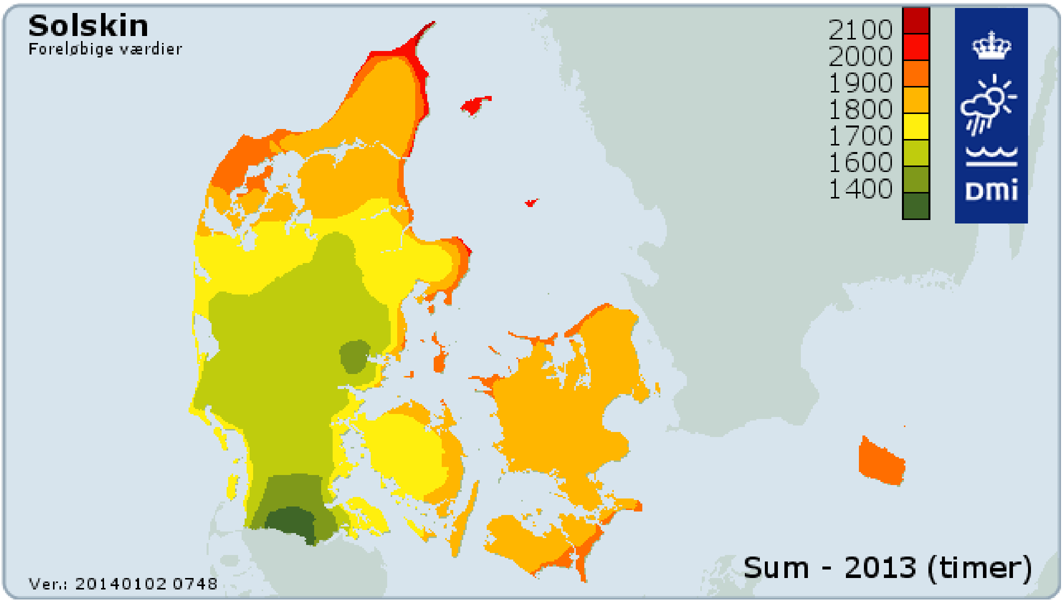


Figure 12. Number of sunshine hours in Denmark in year 2013 (DMI, Vejret i Danmark året 2013, 2013).

Development of solar PV in Denmark

Energinet.dk (2015) states the following table of installed systems in 2012 and 2013. The 2014 figures are not included yet, but judging by another information on Energinet.dk, there is a further development. Since the application of the new solar pool of 20 MW in the public sector was opened, there was within the first seven hours applied for 494 projects on municipal buildings. The pool closed after only one day.

The fact that the focus has changed from household plants to plants in the public sector and in the business sector show that production of electricity is heavily subsidies, and therefore politically controlled, but also that there is a societal interest in the renewable energy production. Energinet.dk expects that there will be 1000 MW installed capacity with an energy output of 867 GWh in 2035.

Solar PV numbers	**2012**	**2013**	**Change**	
Total Solar PV capacity [MW]	**406.9**	**563.4**	**156.5**	**38 %**
Devices 6 kW	377.5	445.5	68.0	18 %
Devices > 6 kW ≤ 50 kW	19.9	45.0	25.1	126 %
Devices > 50 kW < 400 kW	9.5	48.4	39.0	411 %
Devices ≥ 400 kW	0	24.5	24.5	-
Total solar PV cells [quantity]	**76184**	**91407**	**15223**	**20 %**
Devices 6 kW	74815	88397	13582	18 %
Devices > 6 kW ≤ 50 kW	1286	2586	1300	101 %
Devices > 50 kW < 400 kW	83	368	285	343 %
Devices ≥ 400 kW	0	56	56	-
Total Solar PV production [GWh]	**104**	**518**	**414**	**397 %**

(Note: Ratios for MW and amounts are based on Energinet.dk's master data at the end of 2012/2013. Energinet.dk has no measurements of output from net settlement solar cells. The calculation of photovoltaic production from net settlement PV systems are based on an estimate).

There were major changes in the photovoltaic sector in 2012. The link between declining prices for solar cells, various deductions by setting up solar power plant and the possibility of net settlement (net meter system) led to photovoltaic capacity in Denmark increased by over 3500% in 2012 in terms of installed capacity. Changes to legislation and subsidies at the end of 2012 meant that there has been a large increase in photovoltaic capacity in 2013. In all, there were registered 15,223 new solar power plant in 2013 with a total capacity of 156.5 MW. Where the majority (93%) of solar PV installations in 2012 had a capacity of 6 kW or less, there has been an increase in major solar power plant in 2013. The small plants (≤ 6 kW) amounted at the end of 2013 to 79% of the total solar capacity of Denmark.

Energinet.dk has calculated the total solar PV production in Denmark to 518 GWh in 2013, corresponding to approximately 2% of the Danish electricity consumption. Compared with 2012, an increase of nearly 400% is seen, which compares to an increase in solar capacity over the same period of 38%. The explanation for the surge in solar cell production is first and foremost that a large part of the Danish PV systems were installed in the second half of 2012 and therefore successfully delivered full production in year 2013.

Estimation of production from solar PV cells

Energinet.dk does not have information on electricity generation from solar cells. This means that the solar cells production has not yet entered in the electricity accounts of production in Denmark. Production from solar cells have instead acted as a decrease in total consumption. As solar cells have built a considerable volume in Denmark, Energinet.dk has chosen to include an estimated power generation from solar PV for years 2012 and 2013. The calculation of the solar cell production for 2012 and 2013 are based on a model developed by Energinet.dk in order to make forecasts for the operation of the power system. Electricity production from solar PV are aggregated to a total figure for Denmark on the basis of estimated day productions for over 100 distinct areas. The estimation of solar production in these specific areas is based on information on the installed capacity of solar cells in individual areas and forecasts for the average solar radiation per area.

From the end of 2013, Energinet.dk has implemented an improved basis for calculation of PV production in Denmark. In future, the estimation of solar cell production is based on measurements from more than 1000 solar PV plants in Denmark. The new method will be used for environmental reporting for calendar year 2014, but already by the end of 2013 it has been possible to gain access to hourly values for solar cell production as part of Energinet.dk's market data.

Projections for solar PV

Projections for solar PV capacity factors are shown below according to the Technology Catalogue published by the Danish Energy Authority (Energistyrelsen, 2012):

Technology	Photovoltaics: LARGE scale utility systems					
	2015	2020	2030	2050	Note	Ref
Full load hours (kWh/kW)	1,130	1,195	1,233	1,273	J	

These correspond to capacity factors for solar PV of 12.8% for year 2015, 13.6% for year 2020, 14% for year 2030 and 14.5% for year 2050.

For year 2050, Energinet.dk estimates the following numbers (Energinet.dk, 2011):

DK		Max prod (MW)	**Prod (GWh/y)**	**Prod (TWh/y)**	Full-load hours (h/y)	Cf (%)
1	Solar PV	2537	3000	3,0	1182	13%
2	Solar PV	1691	2000	2,0	1183	13%

III.III.V Pattern of RES in the Reference Year

Based on an annual average value of 1.00, wind index for year 2013 is 0.93 (Nielsen, 2015); thus having 2013 as a reference year makes the analysis conservative with regards to the role that wind energy can have in future Danish energy systems. Also, from a wind power point of view year 2013 is an interesting year as there were two hurricanes.

As waves are related to winds, it is reasonable to accept that waves follow the same trends as winds do. And thus, that the wave potential in year 2013 has been a bit lower than the average. This also allows extrapolating the results of this analysis regarding wave energy to future years.

With regards to solar PV, annual average sunshine hours for Denmark are 1495 hours. However, this number has been increasing since 1980, up to a value of 1869h/y in 2003. Year 2013 had 1780 sunshine hours. Although this is a much higher value than the annual average for Denmark, it is only a bit above the average value of sunshine hours for the period 2001-2014 (both years included), which has an average number of sunshine hours of 1732h/y. Based on these average numbers it can be concluded that year 2013 has been a bit higher than an average year for solar PV. This will be taken into account when extrapolating data to future years and in the discussion of results.

III.III.VI Predictability of Wind, Wave and Solar PV

This section provides a summary of current forecasting accuracy for wind, wave and solar PV.

Wind

Extensive work has been carried out for wind forecasting and balancing costs of wind (Holttinen, 2005), (Costa et al., 2008). Kariniotakis et al. (2004a) review the state of the art in short-term prediction of wind power. They reviewed different forecasting models and the results over geographically dispersed sites. They write:

> "Typical forecast accuracies for single wind farms can vary quite dramatically. In the EU ANEMOS project, a comparison of 11 state-of-the-art tools was made for 6 sites in Europe (Martí, 2006), and the comparison shows that the differences between the wind farms, but also between the forecasting models, are quite large. Figure 13 shows the NMAE variation for each site. The forecast errors are generally higher for more complex terrain, and the difference between the tools is also most significant for most complex terrain."

The next three European projects relate to the development of forecasting tools for wind energy. Anemos compared a number of statistical prediction models and developed forecasting software, which utilises neural network (Anemos, 2013). The Anemos project has been continued by Anemos Plus, which aims to identify instruments to implement Anemos forecasts in the best possible grid management and effective power trading (AnemosPlus, 2013). The Safewind project looks into improvement of the forecasts for extreme wind situations (Safewind, 2013).

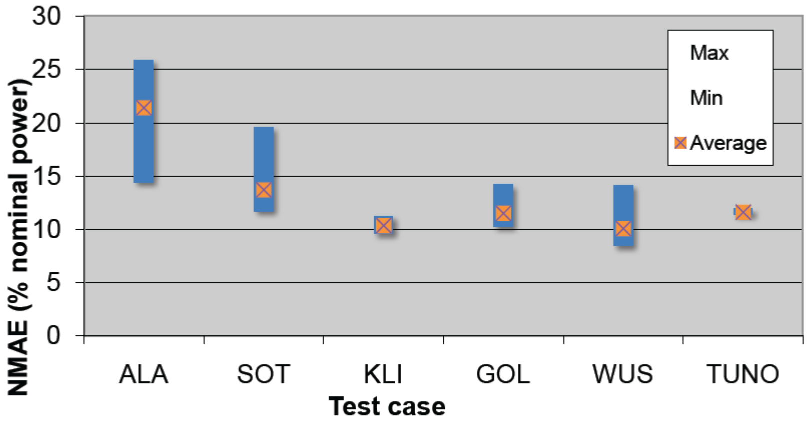


Figure 13. NMAE variation for each test case. 12 hours forecast horizon. Qualitative comparison. The ALA test site is characterized as highly complex, SOT and GOL as complex, KLI and WUS as flat, and TUNO as offshore (Kariniotakis, 2004b).

Wave

One of the most commonly mentioned advantages of wave energy is related to the predictability of waves. Sentences like 'waves are predictable' or 'waves are more predictable than winds' can largely be found on literature. However, a quantifiable number evaluating wave predictability is not easily found on literature and research on wave forecasting is limited to few studies.

Results shown by (Fernández-Chozas, et al., 2013) suggest that for day-ahead forecasts, waves are 23% more predictable than winds, the power output of WECs is 35% more predictable than for wind turbines, and the inclusion of wave energy in a wind-only system reduces balancing costs up to 35%. This would imply annual savings to the Danish system of 13 MEUR (i.e. 95 MDKK/y) and a balancing premium tariff for wave energy of 1.8 EUR/MWh (compared to the current premium tariff of wind turbines of 3 EUR/MWh).

Figure 14 illustrates waves and winds forecasts' accuracy for different forecast horizons, for the significant wave height, the zero-crossing wave period and the wind speed (Fernández-Chozas, et al., 2013). Calculations are based on the comparison of measured and forecast data during 5-winter months of year 2011 in Hanstholm, in the Danish part of the North Sea.

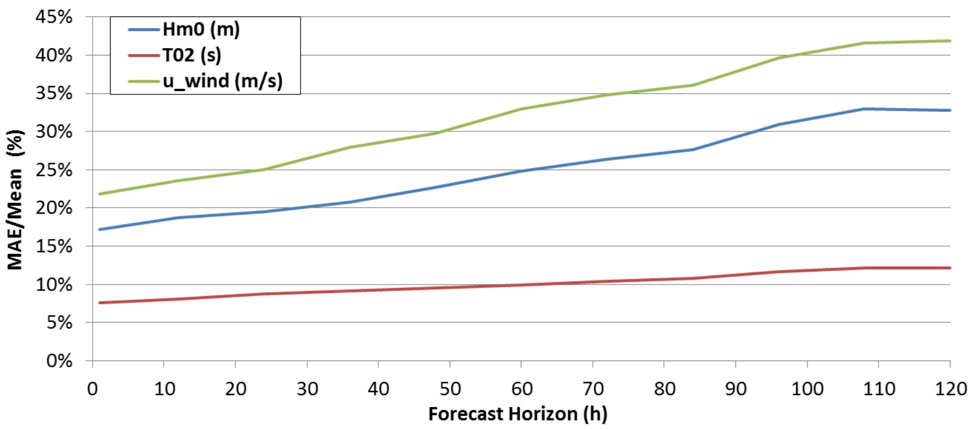


Figure 14. Five-day forecast errors, in terms of *MAE/Mean*, of H_{m0} (in blue), T_{02} (in red) and u_{wind} (in green) at Hanstholm during the study period (Fernández-Chozas, et al., 2013).

Solar PV

One of the experts on solar PV forecasting is Lorenz from University of Oldenburg (Germany). According to her study (Lorenz, Kühnert, Wolff, Hammer, Kramer, & Heinemann, 2014) she concludes that i) forecasting of one single unit differs a lot of forecasting a regional aggregated production, ii) forecasting of solar PV in South Europe is more accurate than in Northern Europe, and that iii) solar PV forecasting in Northern Europe is in the same range of accuracy than wind.

As part of her research work Lorenz has compared three different types of forecasting methods:

1. Clouds index, i.e. cloud motion vector forecast based on satellite data: cloud moving vector (CMV).
2. Persistence: assume that now occurs the same as before.
3. Weather forecasts: numerical weather predictions.

The recommendation on which of the three methods should be used for solar PV production forecasting depends on the time horizon of interest:

- For a time horizon of 0 to 1 hour: Persistence.
- For a time horizon of 1 to 5 hour: Satellite cloud motion forecast.
- For a time horizon of 5 hours to days: NWP numerical weather predictions.

III.IV The Danish Electricity Grid

In order to integrate renewable energy sources like wind, waves and sun, it is necessary to have a stable and developed power grid. Wind power from offshore wind parks and waves are connected to high voltage system while solar generated electricity is mainly connected to the distribution system.

III.IV.I Interconnections: Current and Planned

This section addresses current and planned international electricity connections with neighbouring countries. Interconnections are a key issue in the discussion of Danish security of supply as they are expected to provide much of the reserve capacity required in 100% fossil-fuel free Danish scenarios.

As read in the dedicated report carried out by the Danish Energy Authority on future Danish energy scenarios (Energistyrelsen, 2014): "… *A wind power-based, fully electrified system will have good fuel supply security but will have problems ensuring a reliable electricity supply... In a wind power-based system, reliable electricity supply can be ensured through a combination of low-investment, fast-regulating gas engines/gas turbines that are not given much operating time, and more electrical interconnectors to neighbouring countries*…".

Denmark currently counts with the following interconnections to neighbouring countries and systems (Energinet.dk, 2015). Current and planned interconnections are summarised in Table 4 and illustrated in Figure 15 and Figure 16.

Denmark's interconnections expansion plans are the following (Energinet.dk, 2015): a 400 MW cable is planned for 2019 via the Kriegers Flak offshore wind farm, a 700 MW Cobra Cable is planned for 2020 to connect Jutland and Netherlands, and a 1400 MW Viking Line is planned to connect

Denmark and the UK in 2022. The expansion of the current 1640 MW connection between West Jutland and Germany is planned for year 2021, with 2500 MW, and for year 2025, with 3000 MW.

The Great Belt Power Link, rated at a capacity of 600 MW and inaugurated on September 2010, connects Denmark's two separated transmission systems, of which the eastern one is synchronous with the Nordic system and the western one with the synchronous grid of Continental Europe.

Table 4. Danish International Connections to nighbouring systems as per the end of year 2014 (Energinet.dk, 2015).

International Connections	End year 2014, in MW		*Existing today?*	End year 2035, in MW	
	Export	Import	*(year 2014)*	Export	Import
East Denmark - Sweden (Øresund)	1700	1300	*yes*	1700	1300
East Denmark - Germany (Kontek)	600	600	*yes*	600	600
East Denmark - Germany (Kriegers Flak)	0	0	*no*	400	400
West Denmark - Norge (Skagerrak)	1000	1000	*yes*	1700	1700
West Denmark - Sweden (Konti-Skan)	740	680	*yes*	740	680
West Denmark - Germany	1780	1500	*1640 MW*	3000	3000
West Denmark - Holland (COBRAcable)	0	0	*no*	700	700
West Denmark - England (VikingLink)	0	0	*no*	1400	1400
West Denmark - East Denmark	600	600	*yes*	600	600
Total	**5820**	**5080**		**10240**	**9780**

Taking into account current and planned interconnection capacity, these will provide the following interconnection capacity per country, as depicted in Table 5.

Table 5. Interconnection capacity of Denmark with neighbouring systems as per end of 2035 (Energinet.dk, 2015).

Interconnection capacity of Denmark with neighbouring countries:	Year 2035, in MW		Existing today (year 2014)	
	Export (MW)	Import (MW)	Export (MW)	Import (MW)
Total Germany	4000	4000	2380	2100
Total Sweden	2440	1980	2440	1980
Total Norway	1700	1700	1000	1000
Total Holland	700	700	0	0
Total England	1400	1400	0	0
Total	10240	9780	5820	5080

Figure 15. Existing (in red), under construction (in green) and under planning (in blue) Danish interconnections to neighbouring countries as per November 2013. Import's capacity is shown in MW. (Energinet.dk, 2013).

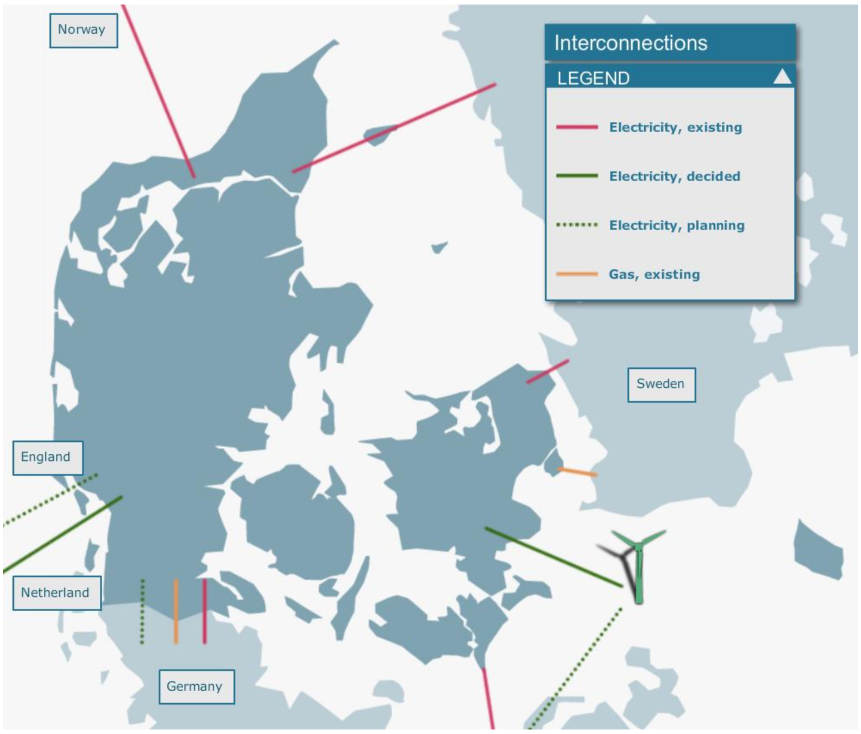


Figure 16. Existing (in red), decided (in green) and planned (in dashed green) Danish interconnections to neighbouring countries, as per September 2015 (Energinet.dk, 2015).

III.IV.II Discussion on Interconnectors and Security of Supply

This subsection provides an overview of whether international interconnectors are a real alternative for Denmark to provide security of supply.

Currenlty Denmark has a diversified system of interconnections to neighbouring systems of Germany, Sweden and Norway. And as described in the section above, it plans to expand the interconnection capacity to the The Netherlands and UK systems. In order to provide security of supply it is important to assess the power balances of neighbouring systems in Danish peak hours.

The System Plan report of 2013 (Energinet.dk, 2013) is the document that summarises Energinet.dk's reporting to the Danish Energy Authority and explains Energinet.dk's most significant activities and focus areas within both the electricity and gas areas. As part of the reporting on interconnections, Figure 17 shows ENTSO-E's projections of power balances of Danish neighbourig countries in the winter period of years 2015 and 2020, respectively.

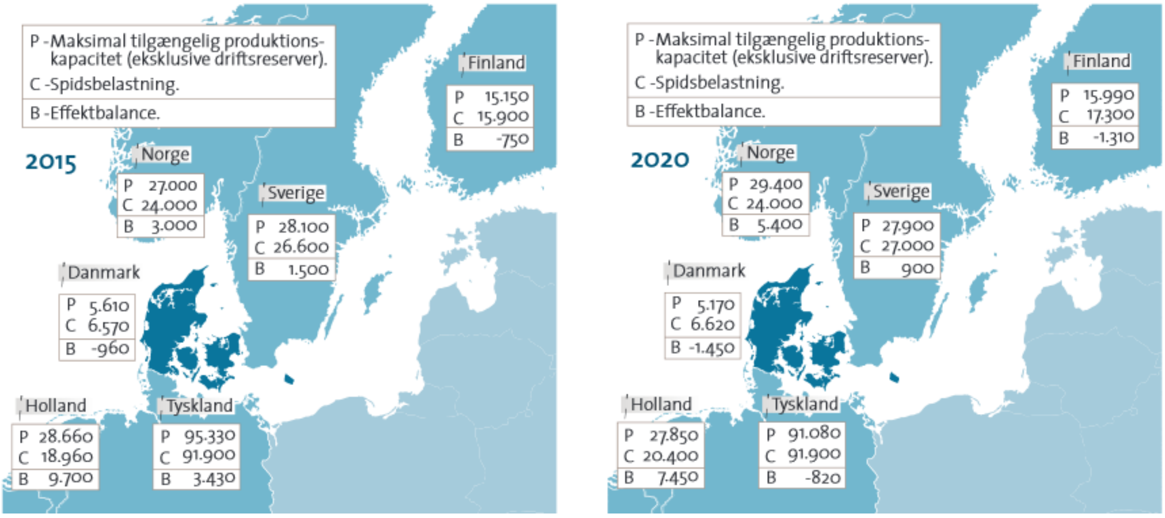


Figure 17: ENTSO-E power balances in MWh/h for the winter period of 2015 and 2020 from the report "ENTSO-E Scenario Outlook & Adequacy Forecast (SO&AF) 2013-2030" (ENTSO-E, 2013). Figures for Denmark are updated based on Energinet.dk's report on Assumptions analysis for 2013. P stands for maximum available production, excluding operational reserves; C for peak load; and B for power balance. This figure belongs to the report (Energinet.dk, 2013).

Figure 17 shows that on hours of peak demand, and under the calculations of ENTSO-E, Denmark depends on imports, and that the tendency is expected to intersify in year 2020 compared to the situation in year 2015 – indeed, year 2013 was the first year where there was not enough back-up capacity in the Danish system to meet demand in hours of low wind (Hvelplund, 2014).

Figure 17 also shows that in year 2020 Germany, together with Denmark, will have more peak consumption than available capacity, and the same situation appears in Finland. Therefore, some of the systems to which Denmark is being interconnected to, might have same stress situations in peak hours as some projections illustrate for the Danish electricity system. This fact posses new challenges in for maintaining Danish security of supply.

III.V Hourly Distribution Data Files

As described before, Denmark is the reference system for the analyses and year 2013 is the reference year. These have allowed having real hourly distribution data as input of the study.

Hour by hour distributions of the different RES have been based on actual measurements whenever possible. For offshore wind, onshore wind and solar PV this has been the case. Data files are based on real hourly measured productions during year 2013, and they do take into account the spatial distribution of RES at a whole Danish level. Such data do not exist for commercial wave energy farms. Consequently, wave production data have been generated from half-hourly wave measurements throughout year 2013 in two sites in the Danish North Sea.

Electriciy consumption data for reference year is also based on actual data, whereas for year 2030 is based on modelled data.

III.V.I Description of Real Data: Wind, Solar PV and Electricity Consumption

Distribution data for offshore wind, onshore wind, solar PV and electricity consumption have the following characteristics:

- They are based on real measured data of year 2013.
- Data covers 1 year.
- Data has hourly resolution, i.e. files have 8760 values.
- When distribution files are used as input of EnergyPLAN model, files have 8784 values. To go from 8760 to 8784 values, the last 24 values of the original dataset are repeated at the end of the file.
- Datafiles do take into account the spatial distribution of offshore wind, onshore wind, solar PV and electricity consumption at a whole Danish level.
- Regarding offshore wind, onshore wind and solar PV, data corresponds to power production in year 2013.
    - Offshore and onshore wind production data have been downloaded from (Energinet.dk, 2015). A note on these data can be found in “Annex II. Note on 2013 Wind Distribution Data”.
    - Solar PV production data has been proceesed and treated from Danfoss database (Danfoss, 2015). A note on these data can be found in “Annex III. Note on 2013 Solar PV Distribution Data”.
- Regarding electricity consumption, data corresponds to electricity consumption in year 2013. Data has been downloaded from (Energinet.dk, 2015).

III.V.II Description of Modelled Data: Wave Data and Electricity Demand Data

Modelled wave power production distribution data have the following characteristics:

- Data covers 1 year.
- Data has hourly resolution, i.e. the file has 8760 values.
- When the distribution file is used as input of EnergyPLAN model, the file has 8784 values. To go from 8760 to 8784 values, the last 24 values of the original dataset are repeated at the end of the file.

Wave power production data has been calculated based on hourly wave measurements in the Danish North Sea (Hanstholm and Horn Rev 3) in year 2013. Having the significant wave height (H_{m0}) and the wave period (T_{02}) as input values, the transfer function has been the Wavestar wave energy converter power matrix (Kramer, et al., 2011) (Kramer, et al., 2013). Precisely, two power matrices of Wavestar have been used. Output values are hourly power production of Wavestar at the two selected locations. Based on these power productions, a distribution file representative of wave production data in the Danish North Sea has been created.

Thus, the datafile takes into account the spatial distribution of wave power along the Danish west coast, but is not representative of the wave potential further offshore in the Danish North Sea.

Compared to other wave energy converters, Wavestar offers two positive features to be selected for this study. First, it holds 4-year experience in testing and operating in Danish waters, and secondly, its power matrix has been designed for a Wavestar operating in the Danish North Sea. It does however have one disadvantage, Wavestar stops production when H_{m0} is above 5 meter. On the other hand wave converters normally have an upper operational limit, forced by a limit in their installed capacity and their storm strategy, so this is a way to account for this loss of production in storm conditions. Alternatively, other technologies could be selected to derive power production data, i.e. Wave Dragon (Tedd , et al., 2006) (Soerensen, et al., 2010) and Weptos (Pecher, et al., 2012) (Pecher, et al., 2014). However, Wave Dragon has not yet developed a power matrix suitable for Danish conditions, and Weptos lacks operation experience in Danish North Sea waters, and thus the power matrix might not be as realistic as Wavestar power matrix.

A background note on the wave distribution file can be found in “Annex IV. Note on 2014 Wave Distribution Data”.

Modelled 2030 electricity consumption distribution data have the following characteristics:

- Data covers 1-year period.
- Data has hourly resolution, i.e. the file has 8760 values.
- When the distribution file is used as input of EnergyPLAN model, the file has 8784 values. To go from 8760 to 8784 values, the last 24 values of the original dataset are repeated at the end of the file.
- Data modelled by Energinet.dk with the following remarks: “this is one example of an hourly power consumption profile for Denmark in year 2035. It only contains the classical consumption pattern. New electricity demands in primarily heat pumps and electric vehicles are expected, but they are considered flexible load and there is not a fixed consumption pattern for them”.
- The datafile takes into account the spatial distribution of the electricity consumption at a whole Danish level.

III.V.III Additional Databases for Wind, Wave and Solar PV Time Series

Annex V describes additional databases useful to obtain hourly distribution data for wind, wave and solar PV in Denmark.

III.VI Definition of Scenarios

For the purpose of the analysis five future different scenarios with different mixes of RES are studied. Year 2030 is the study year and scenarios are based on CEESA2030 Scenario (Lund, 2011), which is constituted by the following features: total RES production of 27.38 TWh/y and total electricity consumption of 41.38 TWh/y, of which 21.85 TWh/y corresponds to classical electricity consumption, 3.93 TWh/y to flexible demand, 4.59 TWh/y to the electricity demand in the transport sector (i.e. electric vehicles), 3.66 TWh/y to consumption of industrial heat pumps, and 7.01 TWh/y to electrolysers and households' heat pumps and electric boilers.

The CEESA project addressed Danish scenarios with a particular focus on renewable energy in the transport system in a context with limited access to bioenergy. CEESA2030 Scenario is comprehensively described in (Lund, 2011) and is based on the smart energy system concept described in (Mathiesen, 2011), (Lund, 2012), (Mathiesen, 2015). The concept of smart energy systems or integrated energy systems is also addressed in this report under "Section IV.III.III System Approach".

Scenarios are built based year 2013 data and on CEESA2030 Scenario. Scenarios are then designed as follows: annual total power production from RES is kept constant at 27.3 TWh/y (same value as in CEESA2030); production from offshore and onshore wind is kept equal or higher than 10.7 and 12.6 TWh/y, respectively, as defined by CEESA2030; and the or capacity factors of each technology are defined by 2013 values. Once productions of each RES are fixed and with the knowledge of the capacity factors, the installed capacity of each RES is calculated.

The six scenarios of the analysis are the following:

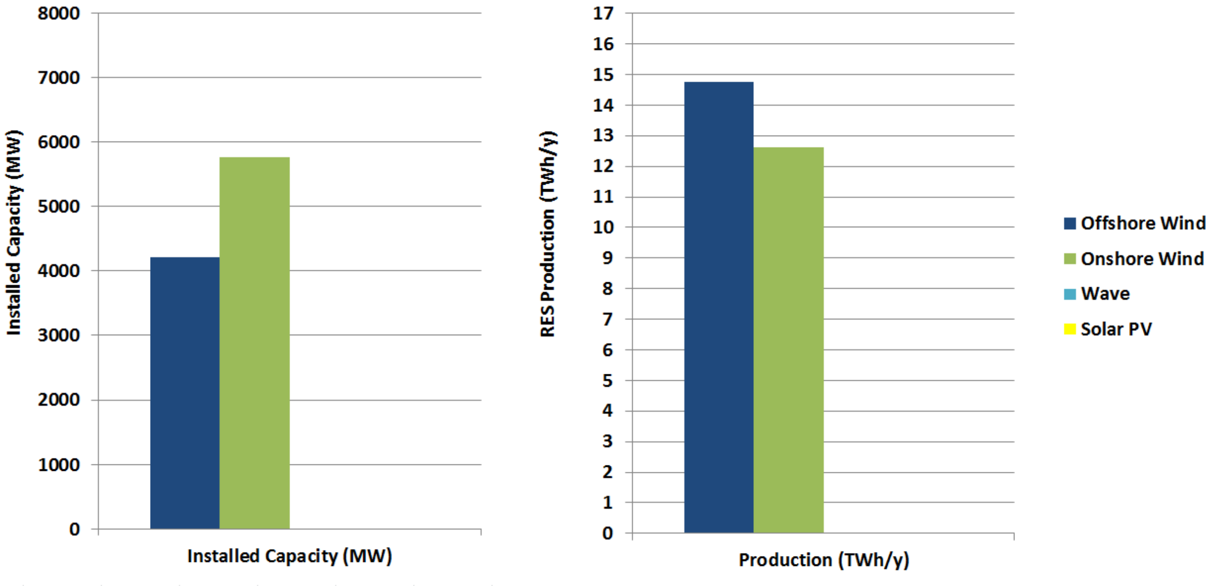
i) Ambitious Offshore Wind Scenario
ii) Ambitious Onshore Wind Scenario
iii) Ambitious Wave Scenario
iv) Ambitious Solar PV Scenario
v) Combined RES Scenario
vi) Århus Wind-Solar PV Scenario

Some of these scenarios can indeed be compared to current and planned future Danish scenarios. The 'Ambitious Onshore Wind Scenario' can be compared to the RES mix in year 2013 in Denmark; the 'Ambitious Offshore Wind Scenario' is representative of ENS Wind 2035 scenario (Energistyrelsen, 2014), and the 'Ambitious Solar PV Scenario' has lot of similarities with CEESA2030 Scenario (Lund, 2011).

The installed capacity (in MW) and annual power production (in TWh/y) of each RES in each scenario are presented below:

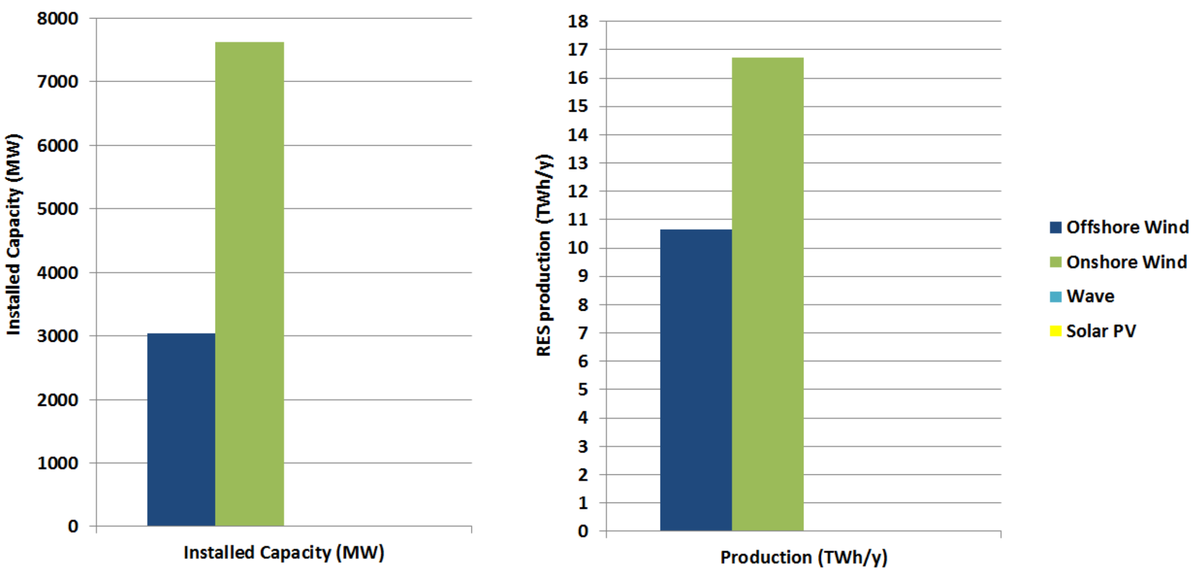
Ambitious Offshore Wind Scenario: in this scenario offshore wind power production is increased to a maximum value, onshore wind power production is kept at CEESA2030 values, and there is no production from wave or solar PV.

Total installed capacity of this scenario is 9977 MW.



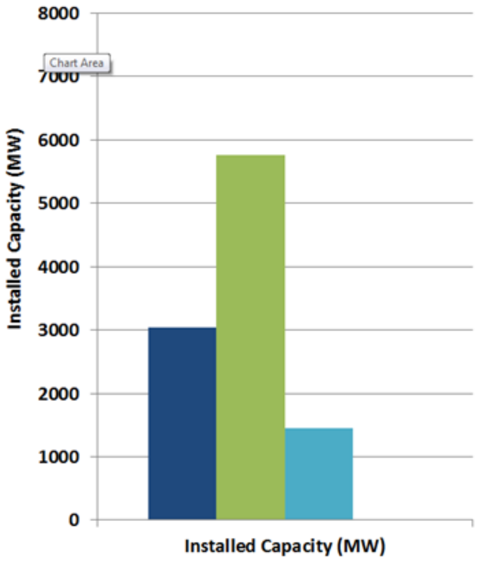
Ambitious Onshore Wind Scenario: in this scenario offshore wind power production is kept at CEESA2030 values, onshore wind production is increased to a maximum value, and there is no production from wave or solar PV.

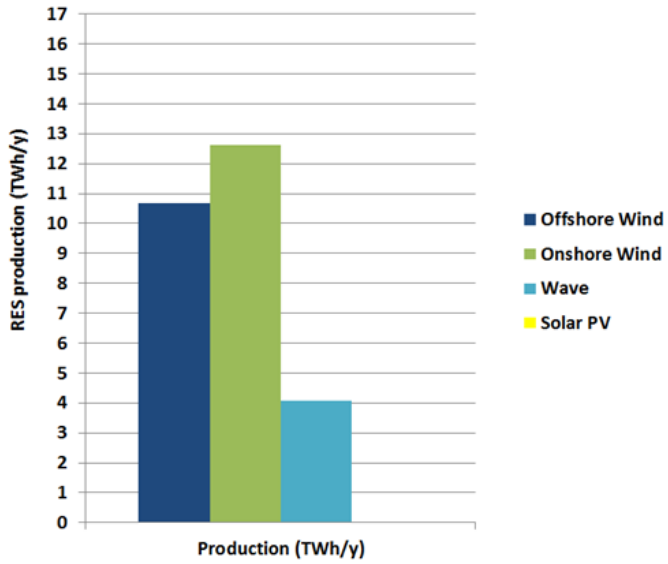
Total installed capacity of this scenario is 10675 MW.



Ambitious Wave Scenario: in this scenario offshore and onshore wind productions are kept at CEESA2030 values, wave production is increased to 4 TWh/y (15% of total RES production), and there is no production from solar PV.

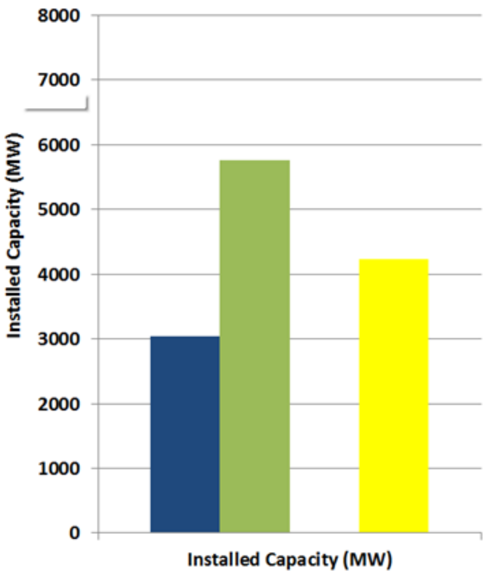
Total installed capacity of this scenario is 10268 MW.

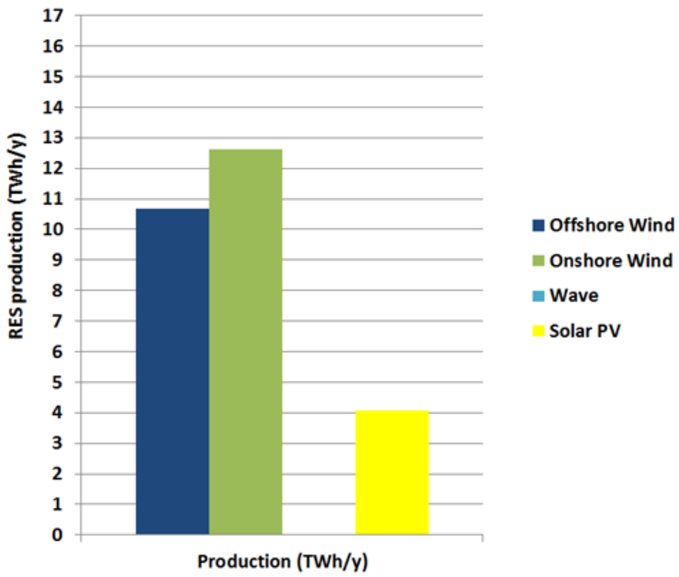




Ambitious Solar PV Scenario: in this scenario offshore and onshore wind productions are kept at CEESA2030 values, there is no production from wave energy, and solar PV production is increased to 4 TWh/y (15% of total RES production).

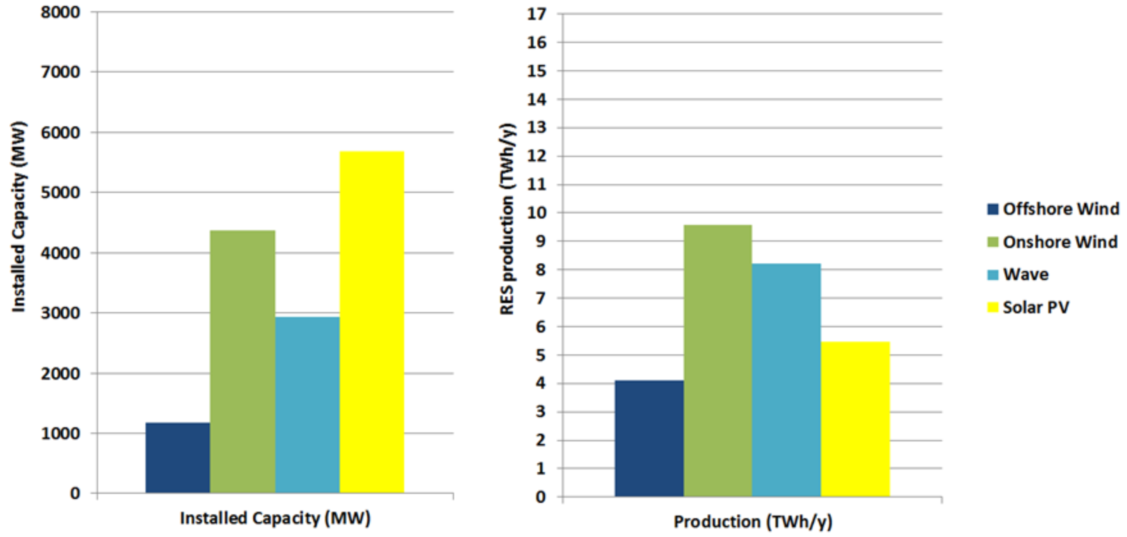
Total installed capacity of this scenario is 13046 MW.





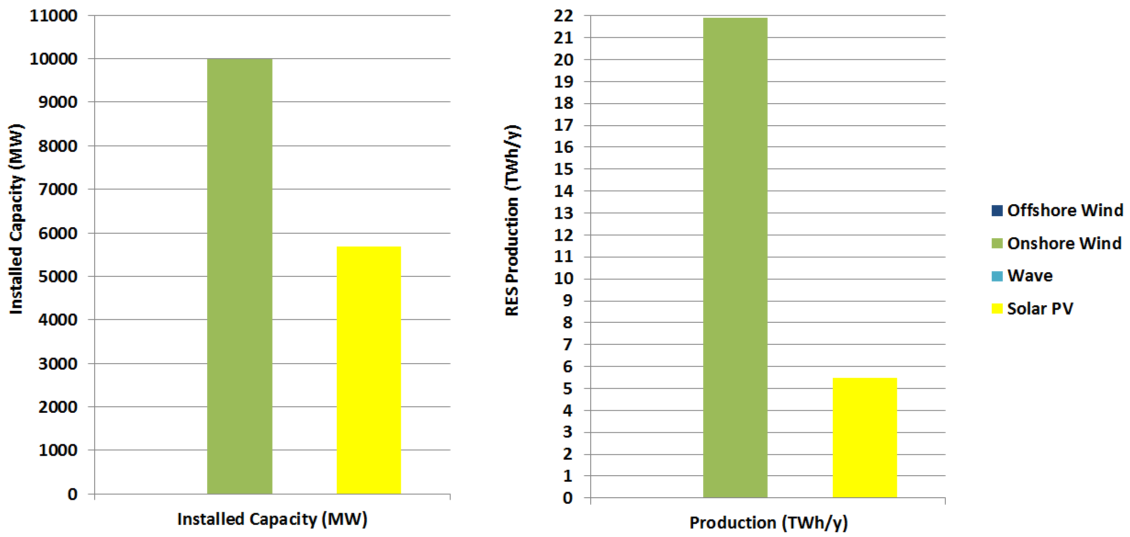
Combined RES Scenario: this scenario is defined based on the findings of (Lund, 2006), which to the author's knowledge, is the first Danish study looking into optimal combinations of the four RES of the project with high RES system penetration. The paper suggests an optimal mix of RES for Denmark when production from RES is above 80% of total production. Lund's analysis is done from a technical point view, where the optimisation parameter is the minimum excess production. In this scenario offshore wind produces 15% of the total RES production, onshore wind 35%, wave 30% and solar PV 20%.

Total installed capacity of this scenario is 14161 MW.



Århus Wind-Solar PV Scenario: this scenario is defined based on the findings of Aarhus University (Heide D., 2010) and (Andresen G., 2012), who investigated a Danish electrical energy system based on 50% renewable energy sources in year 2020, and conclude that the optimal solution is to cover approximately 20% of the energy demand with solar PV and 80% of the energy demand with wind. This study is done from a techno-economic point view, where optimisation parameters are minimum electricity costs and minimum storage.

Total installed capacity of this scenario is 15685 MW.



Chapter IV – Qualitative and Quantitative Assessments

The contribution that variable renewable energies can have to security of supply is assessed through the parameter capacity credit. The aggregated capacity credit of a mix of RES in a system depends on several factors; some of them are related to the power system and others to the RES portfolio. In this way, some factors affect positively, i.e. increase, the capacity credit of a variable RES portfolio in a given system, and others affect it negatively, i.e.e decrease it. Also, it is possible to calculate the capacity credit of a mix of RES.

Accordingly, the contribution that variable renewable energies can have to security of supply is assessed from two different perspectives; firstly, from a qualitative perspective and secondly, quantitatively.

This section (Chapter IV) presents first the parameter capacity credit and the factors that influence it, and afterwards the parameters utilised for the qualitative and the quantitative assessments are introduced. Next section (Chapter V) describes the results of each assessment.

IV.I Capacity Credit

The Capacity Credit (CC), also known as capacity value, is a measure of the contribution that variable renewable energy generation can make to system adequacy.

The aggregated capacity credit of a RE mix in a system depends on several factors:
Some are related to the power system:

- Reliability level of the system.
- Flexibility of the power generation mix (i.e. system's baseload based on mini hydro or on nuclear, system's storage capacity, etc.)
- Penetration level of the RE generation mix in the system.

And some others are related to the RE portfolio and the RE technologies:

- Correlation between RE production and peak demand
- Geographical dispersion of the RE technologies in the system.
- Level of diversification of the renewable energy mix.
- Average capacity factor of the renewable energy technologies.

In this way, the following factors affect positively (i.e. increase) the capacity credit of a variable RE portfolio in a given system (OECD/IEAa, 2011), (EWEA, 2009):

- Demand and RE production are correlated
- Higher RE production when demand peaks
- Lower degree of system security
- Higher capacity factors of the RE mix.
- Using a more diverse mix of renewables because their outputs, being diverse, are more constant overall.
- Lower correlation between the resources in the RE mix.
- Wider interconnection between regional grids, which can smooth the variability of the renewable resources, and may improve alignment between generation and peak demand

- Implementing demand side management
- Using energy storage technologies that are directly linked to variable renewables

As indicated before, results from regional system adequacy forecasts indicate that there is not yet a national TSO standard for the determination of RE's capacity credit (EWEA, 2009). For example, it can be estimated by determining the capacity of conventional plants displaced by the RE mix, whilst maintaining the same degree of system security; or by determining the additional load that the system can carry when RES are added, maintaining the same reliability level. Sometimes the capacity credit of a RE mix is measured against the outage probabilities of conventional plants (EWEA, 2009). In order to address the numerous definitions that the capacity credit parameter receives, "Annex VI. Capacity Credit Definitions" collects additional definitions, all of them having a nearly similar meaning as the definition used in this report).

In the study context, it is calculated as the amount of power variable renewable energies can reliably be expected to produce at the times when demand for electricity is highest (OECD/IEAa, 2011). It is expressed as a percentage of the installed capacity of the renewable generators, where a value of 100% denotes one-for-one substitution with no loss of system reliability and 0% indicates that the variable source can displace no conventional capacity.

IV.II Parameters for the Qualitative Asssessment

As detailed in the subsection before, the factors that directly influence on the capacity credit of a given mix of RES in a given system are the following:

i) Correlation of RES production and demand
ii) Correlation among RES
iii) Diversification of the RES mix
iv) Geographical dispersion of each RES
v) Penetration level of the RES mix in the system
vi) Average capacity factors of the RES in the system

IV.II.I Cross-Correlation Coefficient

For the two first elements of the analysis the parameter cross-correlation coefficient is used. The cross-correlation coefficient evaluates the relationship between two different parameters, i.e. the degree to which the variation in one parameter is reflected in the variation of the other parameter. It varies in the interval [-1, 1], where <-1> indicates perfect negative correlation, <0> indicates no correlation and <1> indicates perfect positive correlation. The cross-correlation coefficient also allows evaluating the average delay between two set of values, which is the time lag (in hours) at which the cross-correlation coefficient reaches a maximum (Fusco, et al., 2010). A comprehensive description of this parameter can be found in "Annex IV. Note on 2013 Wave Distribution Data".

IV.II.II Diversified Renewable Energy Systems

The term diversified renewable systems refers to an energy system composed of various renewable resources, located in a range of areas within the same or in a different energy system. These systems usually embrace solar (thermal and photovoltaic), biomass, wind, wave and tidal generation, or any combination among them.

The two key benefits of diversification are that the variability of the produced power can be decreased, and power availability can be increased. These benefits can be achieved by combining different resources, the more un-correlated the better. Otherwise, when only one resource is available –wind energy for example– these benefits can only be realised by aggregating the power of geographically disperse sites.

The understanding of the properties and characteristics of diversified system has been the focus of recent research in several countries. Following the core idea of this project only the studies covering a combined offshore wind, onshore wind, wave and/or solar PV scenario are investigated.

ECI (2005) examines the variability of waves and tidal currents working individually and combined at different locations in the United Kingdom, and relates them to the demand. Among the conclusions it indicates that a combined wave and tidal scenario harnessing the resources at different sites has smoother variability when compared to the tidal-only scenario, and highlights the least variability in the production in a diversified scenario composed by offshore and onshore wind, wave and tidal current. This study is continued by ECI (2006), and it looks into a hypothetical scenario with offshore wind, wave and tidal energy covering 20% of United Kingdom's demand. It compares the benefits of an offshore wind, wave and tidal scenario with a wind-only scenario, and concludes that the diversified system increases the capacity credit and reduces the variability and the additional balancing costs of the system.

A comparable theoretical research is done in Denmark for the offshore wind farm Horns Rev I, located off West Jutland (Soerensen, et al., 2005). The analysis of co-production of wave and wind proves that the delay in winds and waves reflect in the response of the technologies. Wind turbines reach full production 1 to 6 hours before WECs do, and afterwards WECs continue at full power 6 to 8 hours after the power of offshore wind turbines starts decreasing. The study also discusses the variability of the power output and suggests that the half-hour variability of wind production is 3 times higher than for wave production; and this would strengthen during storm events.

The opportunities of providing all the electricity supply of a French island with offshore wind and wave energy is the study subject of Babarit et al. (2006). The analysis concludes the power outputs of the two resources are too correlated to allow for a self-sufficient renewable power system, unless a storage system is included. With that configuration high independency would be achieved, and the island could then become a net electricity exporter to the mainland.

The cross-correlation between the wave and wind resources is also the study subject of Fusco et al. (2010), with focus on a number of sites around Ireland. In the locations where the correlation is low, the combination of wave and wind energy allows for a more reliable, less variable and more predictable electrical power production than with the individual productions.

Stoutenburg et al. (2010) also look into the aggregate production of offshore wind and wave energy farms in California by studying the cross-correlation between the two resources. Their findings on variability reduction and increase of system reliability go in line with the findings of the previous studies.

Cradden et al. (2011) investigate the same properties of diversified offshore wind and wave systems in three sites around Europe, at EMEC in Scotland, at SEM-REV in France and at the Biscay Marine Energy Platform (BIMEP) in Spain. The study investigates the correlation and the delay between waves and winds, and compares the percentage of time of no production and with full production, and the power variability for different wave and wind scenarios. It also analyses the correlation of the power output of different scenarios with United Kingdom's power demand. All results coincide with those from previous studies and indicate that the best match to fulfil United Kingdom's power demand is by utilising the available wind and wave energy resources.

Lastly, Fernández-Chozas (2013) and Fernández-Chozas et.al. (2013) focus on the opportunities of combining the power production of wave and wind technologies in the same site to provide a continuous power output compared to the individual productions. This is investigated through theoretical and real power productions of WECs and of wind turbines. The most indicative finding is that the combined power output is smoother and provides higher availability than the individual productions: both the peaks and the fast changes found in the individual productions reduce when these are combined, and the percentage of time with null production also reduces to a minimum when wind and wave are combined. Variability reduces up to 31% and the percentage of time with zero production decreases to 6% of the time.

In line with the above studies, this project investigates the opportunities that a diversified RES mix can bring by evaluating the average number of hours per year of null or low production. This leads to some conclusions on the differences among individual RES productions and combined RES productions with regards to power availability.

IV.II.III Average Capacity Factors

2013 distribution data have served for calculating average annual Danish capacity factors of offshore wind (40%), onshore wind (25%), wave (32%) and solar PV (11%). Chapter V discusses the capacity fators of the four RES.

IV.III Parameters for the Quantitative Asssessment

In the quantitative analysis the capacity credit of a RES mix is calculated. The following parameters are taken into account in the calculations.

IV.III.I Study Periods

As of interest to national TSOs and the ENTSO-E, this study examines how well the aggregated production of variable RES aligns with periods during which the system faces a high risk of an outage, i.e. periods of peak demand. Additionally, it is also of interest to investigate how RES production aligns with a subset of periods where electricity demand is low or RES production is high. Accordingly, the study focuses on four different periods (named as follows) during which:

- Electricity demand is maximum and RES production is minimum: Worst periods.
- Electricity demand is maximum: Peak demand periods.
- RE production is maximum: Hi-RES periods.
- RE production is maximum and demand is minimum: Best periods.

IV.III.II Time Spans

Nine different time spans are considered in the analysis of each study period. They are intended to represent the contribution of RES on an hourly basis, intra-day basis, intra-week basis, weekly basis, monthly basis and season basis. Time spans selected for the study are: 1-hour, 3-hour, 6-hour, 12-hour, 1-day, 3-day, 1-week, 1-month and 3-month. For every time span the average value for the indicated consecutive hours is measured (for example, the 3-hour value is calculated as the average value of 3 consecutive hours). Representative time spans do not necessarily need to be consecutive; this is, from the same day or hour as the immediately lower or higher time-span. The selected time span represents the consecutive averaged hour/hours in a year where the case of study occurs.

IV.III.III System Approach

Two system approaches to the capacity credit calculations are implemented: an electricity-only system approach and an integrated energy system approach.

The two approaches consider much differentiated systems. The electricity-only system's approach looks into the electricity sector as an isolated energy system, whereas an integrated energy systems' approach is founded on a holistic system perspective that integrates the consumption in all energy sectors: transport, heat, industry and electricity.

The first approach responds to the traditional analysis, where the focus is put only on the classical electricity consumption. Besides classical electricity consumption, the second approach also takes into account:

- Flexible demand, i.e. smart systems and smart appliances.
- Transport sector, i.e. electric vehicles.
- Heat pumps, i.e. big and industrial heat pumps.
- Electrolysers, including:
  - CO_2 hydrogenation, i.e. producing synthetic grid gas out of carbon recycling and hydrogen electrolysis.
  - Hydrogen.
- Households heat pumps and electric boilers.

Figure 18 represents the main differences between the two systems. The left-hand side diagram illustrates the electricity-only system and the right-hand side the integrated energy system. One of the major differences between the two systems is that in an integrated energy system power production from fluctuating electricity sources can also be used in the transport and heating sector.

According to (Lund, 2015), integrated energy systems or the Smart Energy System concept (Smart Energy Systems, 2015) is essential for 100% renewable energy systems to harvest storage synergies and exploit low-value heat sources. As opposed to, for example, the smart grid concept, which takes a sole focus on the electricity sector, the smart energy system approach includes the entire energy system in its identification of suitable energy infrastructure designs and operation strategies. Focusing solely on the smart electricity grid often leads to the definition of transmission lines, flexible electricity demands and electricity storage as the primary means to dealing with the integration of fluctuating renewable sources. However, these measures are neither very effective nor cost-efficient considering the nature of wind power and similar sources. The most effective and least-cost solutions are to be found when the electricity sector is combined with the heating and cooling sectors and/or the transport sector. Moreover, the combination of electricity and gas infrastructures may play an important role in the design of future renewable energy systems.

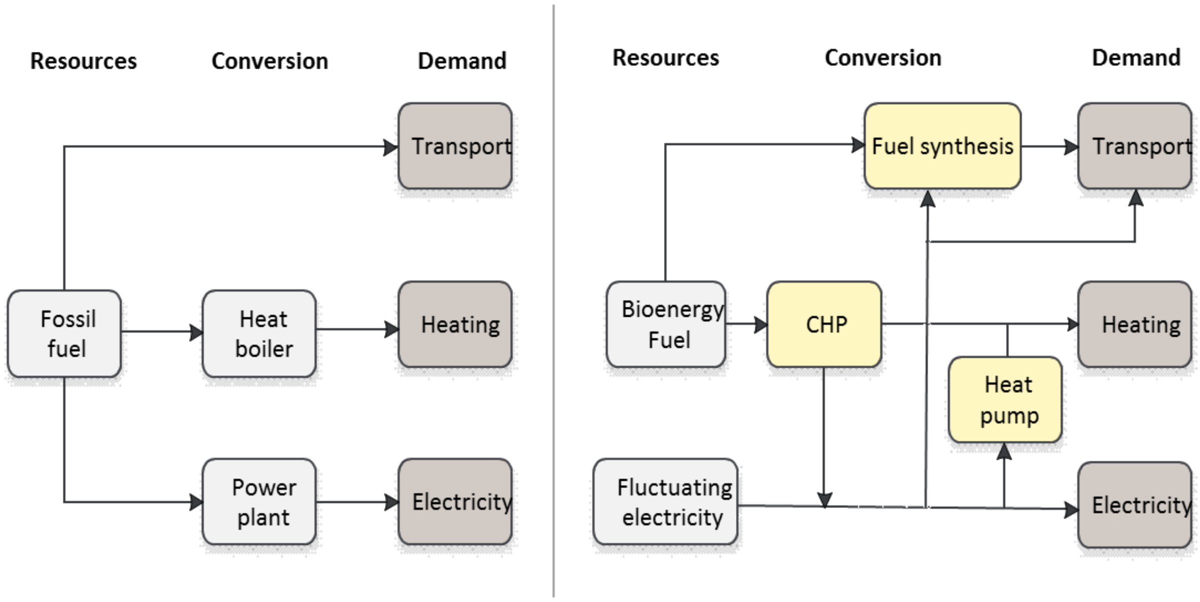


Figure 18. Electricity-only system (left) and integrated energy system (right), (Ridjan, 2015).

IV.III.IV Models

Two models have been used for the analyses, an in-house model developed for the project and EnergyPLAN model.

In-house model

The in-house model has been developed by Consulting Engineer Julia F.Chozas in Excel software.

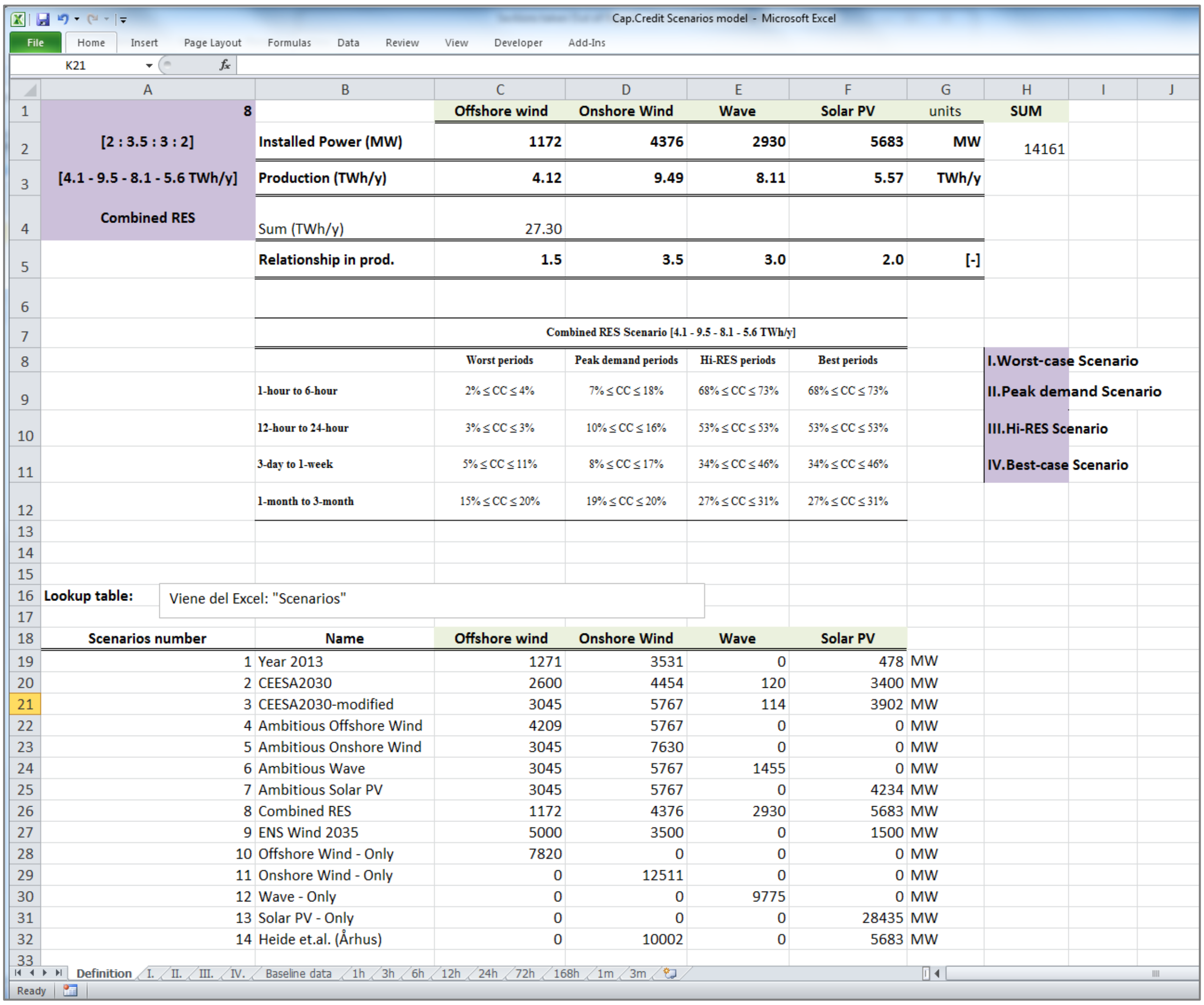
It allows calculating the individual and aggregated capacity credit of a given RES mix in a given system for all the time spans and periods considered in the analysis, and therefore, most of the work has been done with this model.

Input data are hourly RES production and hourly electricity demand, and ouput data the individual and combined capacity credits of the RES in the selected scenarios.

Depending on the type of electricity demand considered, i.e. inflexible or flexible electricity demand, or, in other words, electricity demand as in the electricity-only system or as in the integrated energy system, input hourly distribution files have been extracted from Energinet.dk (as indicated in Chapter III) or have been the output of EnergyPLAN model, respectively. This is due to the fact that EnergyPLAN allows the hourly modelling of integrated energy systems.

Also, all the cross-correlation calculations of RES and of RES with demand have been done in Excel.

Figure 19 shows a screenshot of the in-house developed model that allows calculating the capacity credits of RES in a given scenario.



8		Offshore wind	Onshore Wind	Wave	Solar PV	units	SUM
[2 : 3.5 : 3 : 2]	Installed Power (MW)	1172	4376	2930	5683	MW	14161
[4.1 - 9.5 - 8.1 - 5.6 TWh/y]	Production (TWh/y)	4.12	9.49	8.11	5.57	TWh/y	
Combined RES	Sum (TWh/y)	27.30					
	Relationship in prod.	1.5	3.5	3.0	2.0	[-]	

	Combined RES Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]			
	Worst periods	Peak demand periods	Hi-RES periods	Best periods
1-hour to 6-hour	2% ≤ CC ≤ 4%	7% ≤ CC ≤ 18%	68% ≤ CC ≤ 73%	68% ≤ CC ≤ 73%
12-hour to 24-hour	3% ≤ CC ≤ 3%	10% ≤ CC ≤ 16%	53% ≤ CC ≤ 53%	53% ≤ CC ≤ 53%
3-day to 1-week	5% ≤ CC ≤ 11%	8% ≤ CC ≤ 17%	34% ≤ CC ≤ 46%	34% ≤ CC ≤ 46%
1-month to 3-month	15% ≤ CC ≤ 20%	19% ≤ CC ≤ 20%	27% ≤ CC ≤ 31%	27% ≤ CC ≤ 31%

I.Worst-case Scenario
II.Peak demand Scenario
III.Hi-RES Scenario
IV.Best-case Scenario

Lookup table: Viene del Excel: "Scenarios"

Scenarios number	Name	Offshore wind	Onshore Wind	Wave	Solar PV	
1	Year 2013	1271	3531	0	478	MW
2	CEESA2030	2600	4454	120	3400	MW
3	CEESA2030-modified	3045	5767	114	3902	MW
4	Ambitious Offshore Wind	4209	5767	0	0	MW
5	Ambitious Onshore Wind	3045	7630	0	0	MW
6	Ambitious Wave	3045	5767	1455	0	MW
7	Ambitious Solar PV	3045	5767	0	4234	MW
8	Combined RES	1172	4376	2930	5683	MW
9	ENS Wind 2035	5000	3500	0	1500	MW
10	Offshore Wind - Only	7820	0	0	0	MW
11	Onshore Wind - Only	0	12511	0	0	MW
12	Wave - Only	0	0	9775	0	MW
13	Solar PV - Only	0	0	0	28435	MW
14	Heide et.al. (Århus)	0	10002	0	5683	MW

Figure 19. In-house developed model for calculating the individual and aggregated capacity credit of RES in different scenarios.

EnergyPLAN model

EnergyPLAN has been used to model integrated energy systems. It was chosen because Aalborg University is project partner, and because of its free access. The intention was to compare the results of EnergyPLAN with ther models, but none of them were available.

EnergyPLAN is a modelling tool for advanced energy systems analysis (EnergyPLAN, 2015). It is a time-step simulation tool, scenario based, using a bottom-up approach, which optimises system operation.

EnergyPLAN has been developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark. As a result, it is now a tool that considers a wide variety of technologies, costs and regulations strategies for an energy system.

The main purpose of the tool is to assist the design of national or regional energy planning strategies under the "Choice Awareness" theory (Lund, 2010), by simulating the entire energy-system: this includes heat and electricity supplies as well as the transport and industrial sectors. All thermal, renewable, storage/conversion, transport and costs (with the option of additional costs) can be modelled by EnergyPLAN. It is a deterministic input/output tool and general inputs are demands, renewable energy sources, energy station capacities, costs and a number of different regulation strategies for import/export and excess electricity production.

Outputs are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity. In the programming, any procedures which would increase the calculation time have been avoided, and the computation of 1 year requires only a few seconds on a normal computer. EnergyPLAN optimises the operation of a given system as opposed to tools which optimise investments in the system (Connolly, Lund, Mathiesen and Leahy, 2010).

EnergyPLAN simulates the energy system on an hourly basis over one year. The hourly time-step is essential to ensure that intermittent renewable energy is capable of reliably meeting the demands for electricity, heat and transport.

Figure 20 shows the flow chart of resources, conversion technologies and demands considered in EnergyPLAN.

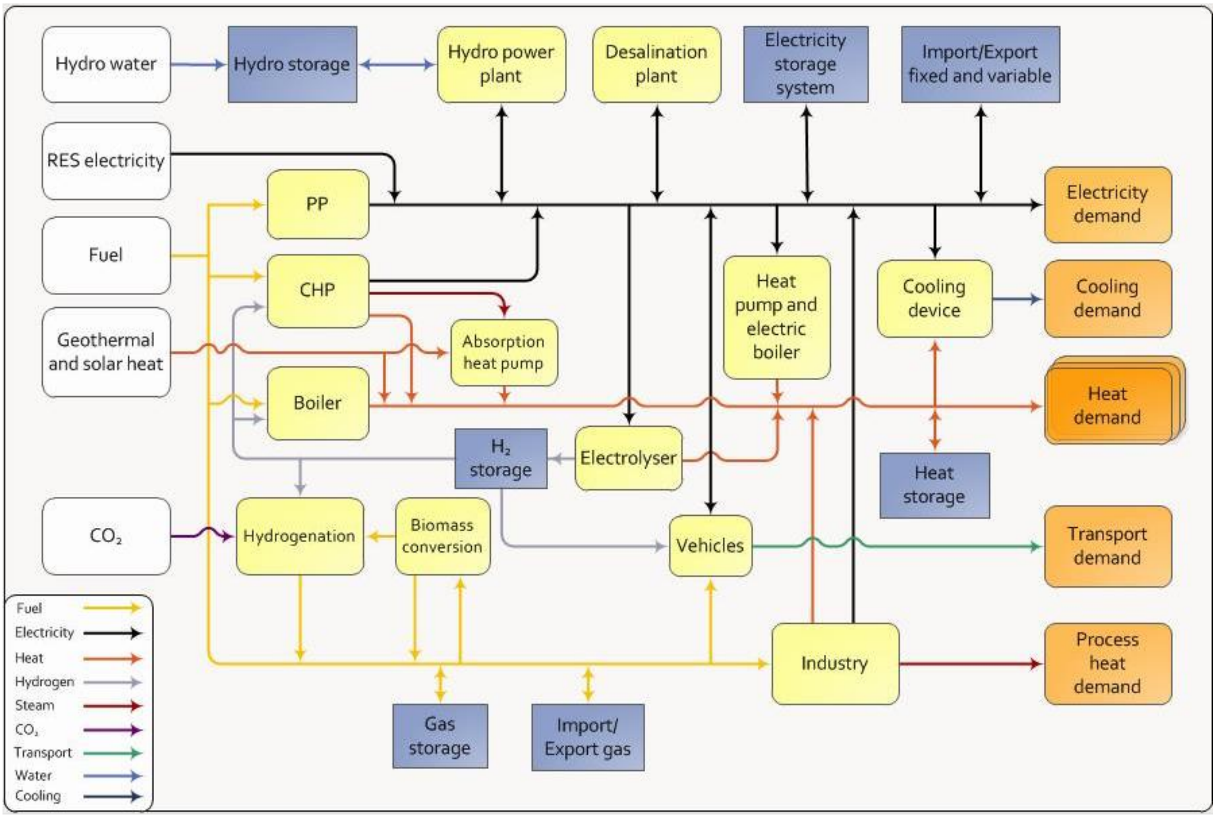


Figure 20. Flow chart of resources, conversion technologies and demands considered in EnergyPLAN (EnergyPLAN, 2015).

IV.III.V Modelling Background Data

The following remarks apply to the modelling exercises:

- The modelling is deterministic.

- Classical Electricity Demand distribution data in <A) Electricity-only system approach> is:
    - For "Year 2013 Scenario", the electricity demand of year 2013.
    - For all other scenarios, the electricity demand of year 2035.

- Distribution data files in <B) Integrated energy system> are the same distribution files as in CEESA2030 analysis, except for the following ones:
    - Electricity demand, changed to electricity demand of year 2035.
    - Offshore wind, changed to distribution data for offshore wind in year 2013.
    - Onshore wind, changed to distribution data for onshore wind in year 2013.
    - Wave, changed to distribution data for wave power production in year 2013.
    - Solar PV, changed to distribution data for solar PV production in year 2013.

- <A) Electricity-only system approach> represents the classical electricity demand:
    - In year 2013, this is 33.5 TWh/y.
    - In CEESA2030, this is 21.85 TWh/y.

- <B) Integrated energy system approach> includes:
    - Total electricity demand in CEESA2030 is 41.38 TWh/y.

- It might be unrealistic or biased the fact that in the scenarios of the analysis the expected annual RES production exceeds classical electricity demand (i.e. in CEESA2030 scenario RES production equals 27 TWh/y and the classical electricity demand is about 21 TWh/y). Nevertheless, this assumption has been drawn in accordance with national plans. Danish Energy Authority's projections as in ENS Wind 2035 Scenario, state that RES production equals 32 TWh/y and classical electricity demand about 28 TWh/y. Conclusions to be drawn in this report are based on these background data.

- The modelling (both for the in-house model and in EnergyPLAN) consideres no bottlenecks between West and East Denmark (i.e. as if Denmark was a copper plate).

- Simulations carried out in EnergyPLAN model: A set of six diffrenet simulations (named hereafter Case Studies) are carried out with EnergyPLAN model. The three first simulations obey to a technical simulation and the last three to a market economic simulation. The differences among the three case studies analysed are in the interconnectors' capacity available for exports and imports.

    - Technical Simulation Strategy 3: this simulation balances both heat and electricity demands, and reduces CHP also when partly needed for grid stabilisation.
        I. Case study I: no interconnectors capacity, i.e. export/import = 0 MW.
        II. Case study II: interconnectors capacity as by end of year 2013, i.e. export/import = 5820 MW / 5080 MW.

III. Case study III: interconnectors capacity as expected in year 2035, i.e. export/import = 10240 MW / 9780 MW.

- Market Economic Simulation:
  IV. Case study IV: no interconnectors capacity, i.e. export/import = 0 MW.
  V. Case study V: interconnectors capacity as by end of year 2013, i.e. export/import = 5820 MW / 5080 MW.
  VI. Case study VI: interconnectors capacity as expected in year 2035, i.e. export/import = 10240 MW / 9780 MW.

Chapter V – Results and Discussion

This section presents and dicusses the set of results of the qualitative and the quantitative assessments. Firstly, qualitative results on the factors that positively contribute to increase the capacity credit of RES are provided. Secondly, quantitative results are given and the capacity credits of RES in different 2030 scenarios are calculated. Lastly, the results of both analyses are discussed.

V.I Results for the Qualitative Assessment

This subsection provides the results of the qualitative assessment of the factors that increase the capacity credit of RES. This section examines the cross-correlation among RES and the cross-correlation of RES production and demand. The less correlated RES are to each other, the higher the capacity credit of the RES mix will be. With regards to the electricity demand it is the opposite; once RES are combined, the more correlated RES' production is to the electricity demand, the higher the capacity credit of the RES mix is.

V.I.I Correlation of RES Production and Classical Electricity Demand

The cross-correlations at a 0-hour time lag between individual and combined RES production and classical electricity consumption are studied here. As electricity is generally not stored, and therefore RES production and electricity consumption happen at the same time, it is interesting to investigate the cross-correlation between RES production and electricity consumption at a 0-hour time lag, i.e. cross-correlation at t=0.

The analysis investigates the following questions:

1. What is the cross-correlation between the individual production of each RES and the classical electricity consumption?
2. Does cross-correlation between RES production and classical electricity demand increase when the different RES are combined?
3. Which of the relationships of the study among RES maximises the correlation between RES production and demand?

Table 6 shows the cross-correlation between RES production and classical electricity demand when the four RES of the analyses (offshore wind, onshore wind, wave and solar PV) are alone or combined in a RE mix. The power production of each RES is indicated by the number in brackets; e.g. [a - b - c - d] denotes the power production of [offshore wind - onshore wind - wave - solar PV], respectively.

Table 6 shows that onshore wind and solar PV productions are the most correlated to the electricity demand, with cross-correlations of 0.14 and 0.13, respectively. Offshore wind and wave production are similarly cross-correlated with the electricity demand, with a value of 0.07. When RES are combined and independently of the RES mix analysed, generation and demand are positively correlated with values above 0.10 and below 0.20.

Among the scenarios studied, the highest cross-correlation factor is achieved by combining onshore wind and solar PV production in an 80%-20% power production relationship, as suggested by (Heide D., 2010). In this scenario the cross-correlation factor equals 0.19. The second largest cross-correlation factor is achieved by combining the four RES in a relationship as suggested by (Lund, 2006). Due to the fact that this scenario includes offshore wind in the generation mix, this scenario is more representative of the RES mix in the Danish system, and it has a cross-correlation factor of 0.17. These numbers can be compared with the cross-correlation factor of RE production and demand in year 2013, of 0.13.

Table 6. Cross-correlation factors between different scenarios of RES and electricity demand for a 0-hour delay. Numbers in brackets indicate RES production of [offshore wind - onshore wind - wave - solar PV], respectively.

Scenarios	Cross-Correlation
Year 2013 [1271 : 3531 : 0 : 478.3 TWh/y]	0.13
Ambitious Offshore Wind Scenario [14.8 - 12.5 - 0 - 0 TWh/y]	0.11
Ambitious Onshore Wind Scenario [10.7 - 16.6 - 0 - 0 TWh/y]	0.12
Ambitious Wave Scenario [10.7 - 12.5 - 4 - 0 TWh/y]	0.12
Ambitious Solar PV Scenario [10.7 - 12.5 - 0 - 4.2 TWh/y]	0.16
Combined RES Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]	0.17
Offshore Wind – Only	0.07
Onshore Wind – Only	0.14
Wave – Only	0.07
Solar PV – Only	0.13
Århus Wind-Solar PV Scenario [0 - 21.7 - 0 - 5.6 TWh/y]	0.19

V.I.II Correlation among RES

Here it is investigated the cross-correlation factor among RES (i.e. wind production, wave production and solar PV production). Study year is 2013. The cross-correlation coefficient is utilised for the study, and it being a function of a time lag, the temporal relationship between the two studied variables can be observed.

As shown in Figure 21 offshore wind is high correlated to onshore wind production (*cross-correlation(0)=0.85*), and the correlation is maximum for a zero delay.

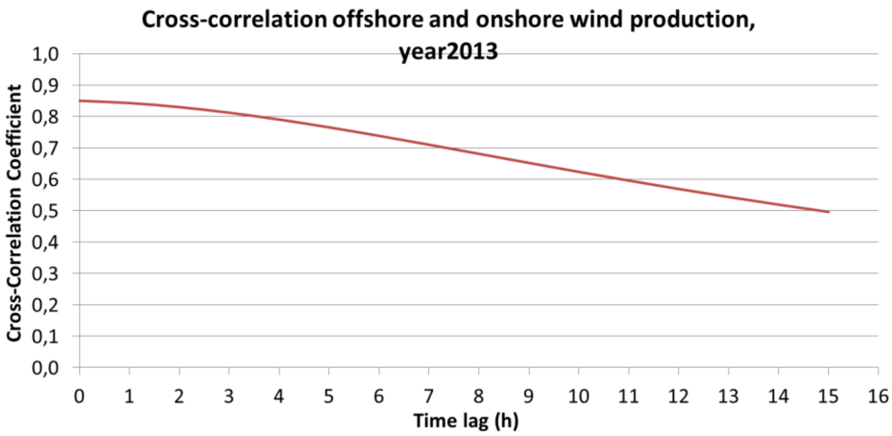


Figure 21. Cross-correlation coefficient between offshore wind and onshore wind production in Denmark in year 2013, for different time delays.

The cross-correlation between winds and waves in Denmark is evaluated by comparing offshore and onshore wind production, respectively, with wave production, in year 2013. Results are shown in Figure 22 and Figure 23 below.

Both figures indicate there is high correlation between wind and wave power production, which is explained by the fact that waves are created by winds. Cross-correlation factor is between 0.6 and 0.7 for a zero time lag, i.e. *cross-correlation(0)*. The point in time when *cross-correlation(t)* is maximum indicates the *average* phase shift between wind and wave power production. This is especially important in order to integrate different energy sources in the electricity system.

Figures below show that the average delay between wind and wave power production is in between 1 to 2 hours for offshore wind production, and 1 to 4 hours for onshore wind production. Maximum cross-correlation coefficients reach 0.68 and 0.62, respectively. Figures below also shows that for a delay up to 7-8 hours, the correlation remains high (*cross-correlation>0.6*).

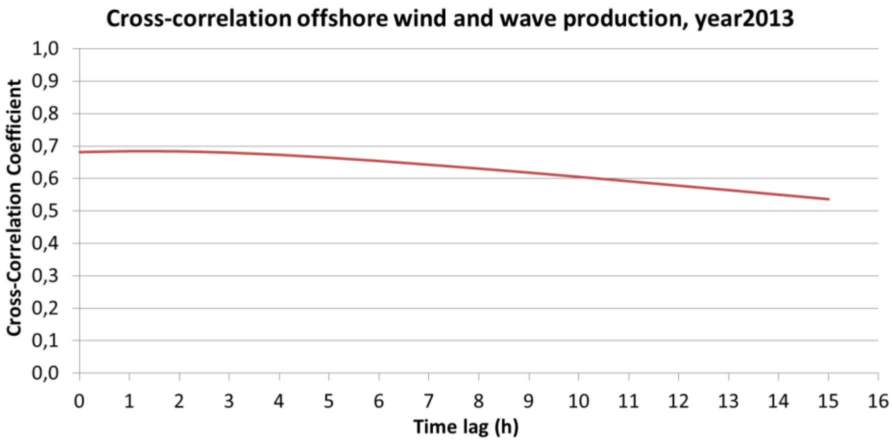


Figure 22. Cross-correlation coefficient between offshore wind and wave power production in Denmark in year 2013, for different time delays.

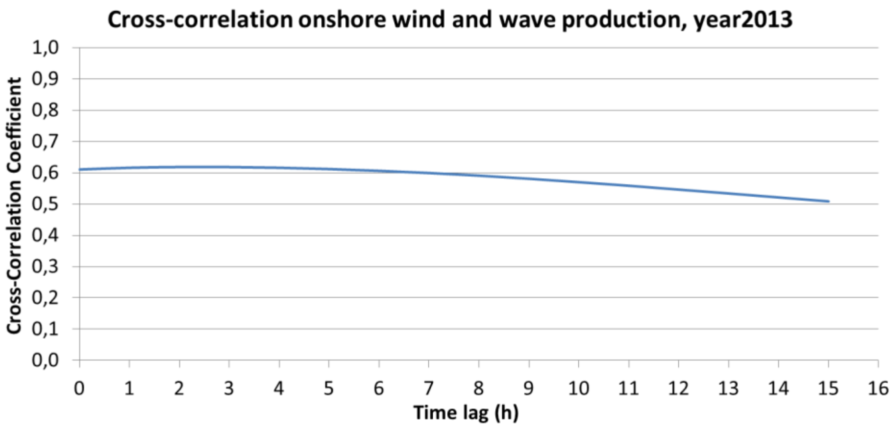


Figure 23. Cross-correlation coefficient between onshore wind and wave power production in Denmark in year 2013, for different time delays.

Fernandez-Chozas et. al. (2013) compare the degree to which the wind speed and the significant wave height were related during a 5-month winter period in Hanstholm (on the North-west coast of

Denmark). Final results indicated a cross-correlation between winds and waves above 0.8. The *average* phase shift between winds and waves at the study site and for the study period was about 2-3 hours Figure 24.

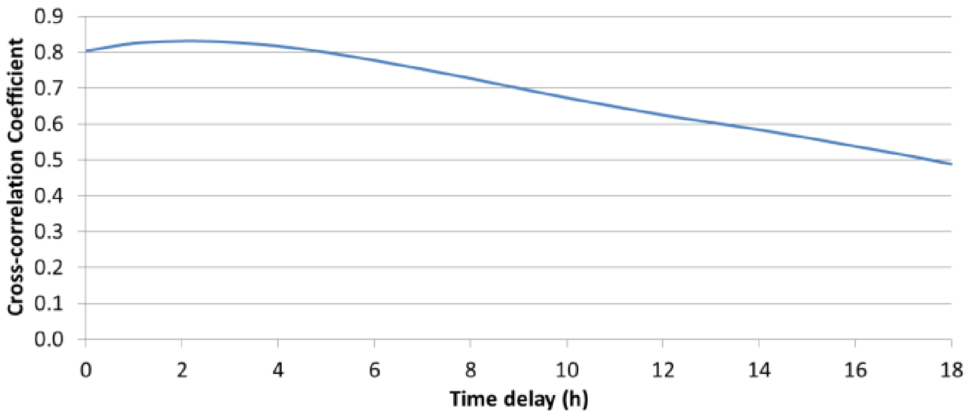


Figure 24. Cross-correlation coefficient between winds and waves at Hanstholm for different time delays. Only wind speeds with MWD_{wind} in the intervals [0,45) and (220,360] are considered. Data from January to May 2011.

The difference between those results and the ones presented here relate to the data analysed. Firstly, Figure 22 and Figure 23 represent the whole Denmark, whether Figure 24 represents only one single location. Hence, results shown in the upper figures are influenced by the smoothing effects of geographical dispersion. Also, upper figures represent power production, whereas the lower figure is based on raw wind and wave parameters. The smoothing effect of the technologies in converting the raw resource into electricity can also be seen.

Figure 25, Figure 26 and Figure 27 below shows solar PV is totally uncorrelated with wind production, independently of it being offshore wind, onshore wind or total wind production. The negative values indicate negative correlation.

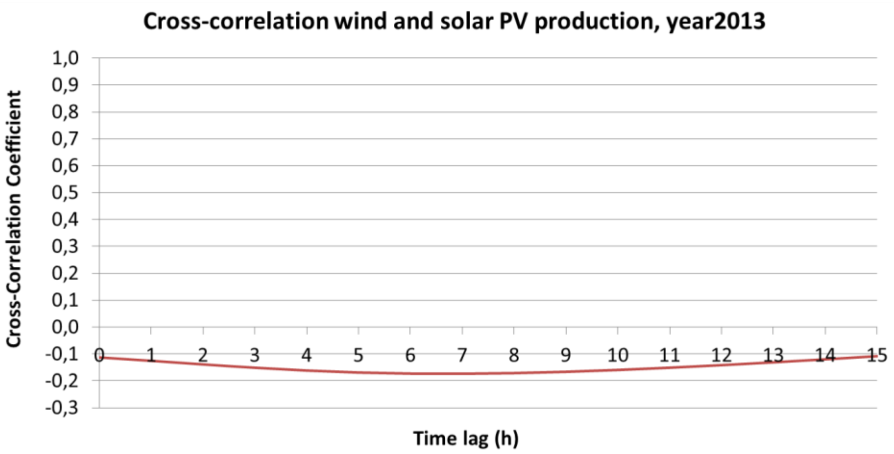


Figure 25. Cross-correlation coefficient between wind and solar PV production in Denmark in year 2013, for different time delays.

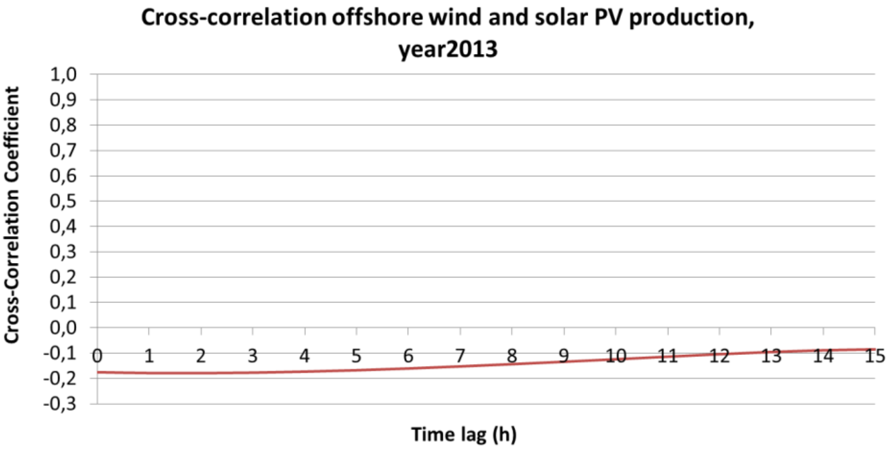


Figure 26. Cross-correlation coefficient between offshore wind and solar PV production in Denmark in year 2013, for different time delays.

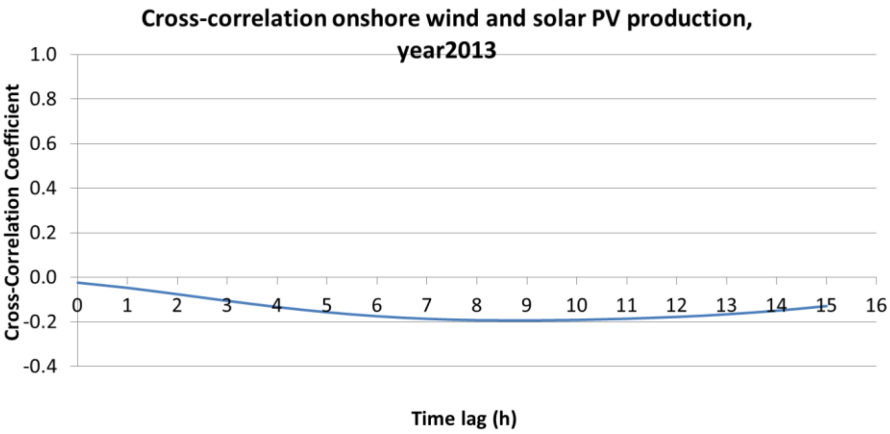


Figure 27. Cross-correlation coefficient between onshore wind and solar PV production in Denmark in year 2013, for different time delays.

A similar pattern can be observed by studying the cross-correlation between wave and solar PV. Solar PV production is totally uncorrelated with wave production, with minimal negative correlation.

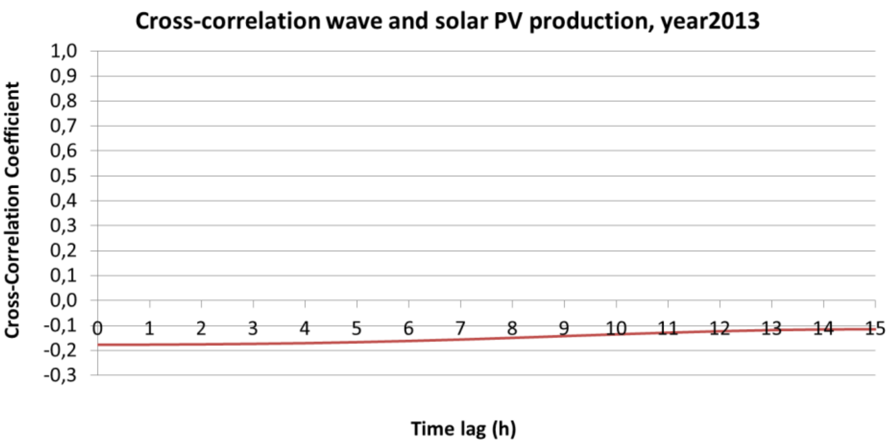


Figure 28. Cross-correlation coefficient between wave and solar PV production in Denmark in year 2013, for different time delays.

Table 7 summarises the results presented above. Offshore wind, onshore wind and wave are highly correlated, and solar PV is uncorrelated. Offshore wind is high correlated to onshore wind production, i.e. a factor of 0.85, and the correlation is maximal for a zero-hour delay; there is also high correlation between wind and wave power production, which is explained by the fact that waves are created by winds; cross-correlation factors are between 0.6 and 0.7 for a zero-hour time lag. The average delay between wind and wave production is in between 1 to 2 hours for offshore wind production, and 1 to 4 hours for onshore wind production. On the other hand, solar PV is low correlated with offshore wind, onshore wind or wave production, presenting a low negative correlation.

Table 7. Cross-correlation coefficient between two pair of RES. The maximum value is shown, as well as the delay, in hours, when correlation is maximum (in brackets).

	Offshore wind	Onshore wind	Wave	Solar PV
Offshore wind	1	0.85 (t=0 h)	0.68 (t=1-2 h)	-0.18 (t=1-2 h)
Onshore wind	-	1	0.61 (t=2-4 h)	-0.19 (t=8-9 h)
Wave	-	-	1	-0.18 (t=0-1 h)
Solar PV	-	-	-	1

V.I.III Diversification of the RES Mix

The opportunities that a diversified RE mix can bring are evaluated by the average number of hours per year of null or low production. Accordingly, the tables below states:

i) number of hours per year with no production from RES
ii) number of hours per year with a production below 1% of total production
iii) number of hours per year with a production below 5% of total production

Calculations are done of each RES operating alone (Table 8), combined in two (Table 9), combined in three (Table 10) and for the four of them together (Table 11). Calculations are based on year 2013 data.

Table 8. Average number of hours per year with different production patterns when each RES works alone.

Hours per year when,	Offshore wind	Onshore wind	Wave Prod.	PV Prod.
Production = 0	4 h/y	0 h/y	45 h/y	4232 h/y
Production <1% max. prod.	163 h/y	309 h/y	132 h/y	4613 h/y
Production <5% max. prod.	877 h/y	1505 h/y	1094 h/y	5509 h/y

Table 9. Average number of hours per year with different production patterns when each RES is combined in two, in a 50% power production relationship.

	Offshore wind & Wave	Onshore wind & Wave	Wave & Solar PV	Offshore wind Onshore wind	Offshore wind Solar PV	Onshore wind Solar PV
Hours/year Production = 0	0	0	25	0	1	0
Hours/year Production <1%	271	311	529	519	512	654
Hours/year Production <5%	2422	2613	2653	2786	2518	3252

Table 10. Average number of hours per year with different production patterns when each RES is combined in three.

	Offshore wind & Onshore wind & Wave	Offshore wind & Onshore wind & Solar PV	Offshore wind & Wave & Solar PV	Onshore wind & Wave & Solar PV
Hours/year Production = 0	0	0	0	0
Hours/year Production <1%	251	376	204	252
Hours/year Production <5%	2510	2424	1995	2399

Table 11. Average number of hours per year with different production patterns when the four RES are combined together.

	Offshore wind & Onshore wind & Wave & Solar PV
Hours/year Production = 0	0
Hours/year Production <1%	190
Hours/year Production <5%	2070

Danish RES strategies envision scenarios with high penetrations of offshore and onshore wind, small amounts of solar PV and almost none wave power (Energistyrelsen, 2012), (Energinet.dk, 2011), (Energinet.dk, 2015). Provided that the Danish system at least will have an offshore-onshore wind RE mix, the impact of including wave and solar PV in that mix is reviewed in Table 12.

Table 12. Average number of hours per year with different production patterns for different combinations of RES.

Hours per year when,	Off- and on-shore wind	Off- and on-shore wind, and wave	Off- and on-shore wind, and PV	Off- and on-shore wind, wave and PV
Production = 0	0 h/y	0 h/y	0 h/y	0 h/y
Production <1% max. prod.	519 h/y	251 h/y	376 h/y	190 h/y
Production <5% max. prod.	2786 h/y	2510 h/y	2424 h/y	2070 h/y

Results show that among the scenarios analysed, the renewable energy mix that combines offshore wind, onshore wind, wave and solar PV is the one that reduces to a minimum the number of hours per year with a production below 1% of total production, and the number of hours per year with a production below 5% of total production, with numbers of 190 h/y and 2070 h/y, respectively. The combined offshore and onshore wind energy system presents numbers of 519 h/y and 2786 h/y, respectively.

An interesting finding, which relates to the conclusions from the quantitative analysis, is that the number of hours per year with no production from RES is as low as 0 h/y in most of the scenarios analysed.

V.I.IV RES Geographical Dispersion

Other elements influencing the capacity credit of a given RES mix in a given system are the geographical dispersion of each RES and the penetration level of RES in the system. With regards to RES geographical dispersion, offshore and onshore wind are well-distributed over the whole Denmark, and this is the same for solar PV. The comparison between total wind production (aggregated production of off- and on-shore wind) in West and East Denmark shows an average delay between the two regions of 2-3 hours. For solar PV such an average delay does not exist. For wave energy the picture is different. Wave energy harnessing technologies will be placed in the Danish

North Sea, i.e. West Denmark. Wave energy geographical dispersion can however be achieved by harnessing the waves of areas further offshore, i.e. up to 200 km offshore.

V.I.V RES Penetration Levels

Current penetration levels of RES in Denmark are high (above 40% of total annual production), and projections aim for this number to increase. By 2020, 50% production from RES is projected, and by 2050 this number is expected to increase to 100%.

V.I.VI Average Capacity Factors of RES in Denmark

Background values of this project are year 2013 average Danish capacity factors, where $Cf_{offshore\ wind}$ (40%) > Cf_{wave} (32%) > $Cf_{onshore\ wind}$ (25%) > $Cf_{solar\ PV}$ (11%).

Project results are dependent on the distribution data selected and the average capacity factors of each RES. Accordingly, this subsection reviewes the evolution and projection of capacity factors of each RES.

Average Capacity factors of wind power in Denmark

Figure 29 shows the capacity factors for Danish wind turbines in the period 1980-2011 (Bach, 2012). The average capacity factors for each year tell a story about technological improvements and wind variations. The chart is based on 4978 existing wind turbines. Turbines being commissioned or decommissioned during a year are excluded. 404 turbines operated offshore in 2011.

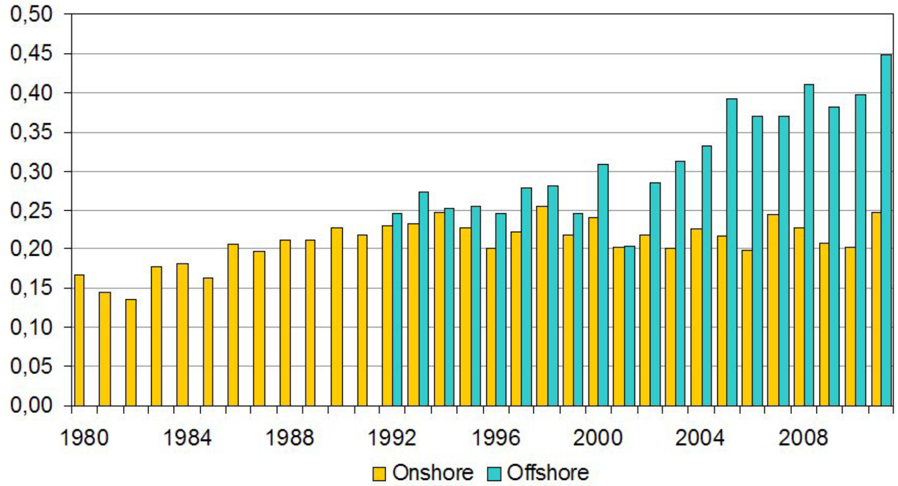


Figure 29. Capacity factors for wind power in Denmark (Bach, 2012)

From year 2000 and beyond, onshore wind capacity factors range between 20% and 25%, and offshore wind capacity factors between 28% and 45%, being one Cf of 20%.

Horns Rev 2 offshore wind farm (inaugurated in 2009) with a nominal total capacity of 209 MW (93 wind turbines each of 2.3 MW), achieved in 2011 one of the highest capacity factors for offshore wind farms at Cf=46.7% (having produced over 1.5 years 1.278 GWh).

According to Energinet.dk (Energinet.dk, 2014), average capacity factors of new offshore wind turbines in Denmark are of 45%, and for new onshore wind turbines of 30%.

Projections for onshore wind capacity and offshore wind average capacity factors for year 2030 according to the Danish Energy Authority (Energistyrelsen, 2012) are of 36.5% for onshore wind and 50-52% for off hore wind.

Energinet.dk (Energinet.dk, 2011) estimates the following numbers for year 2050: $Cf_{offshore\ wind}$ = 41%-49% (but for Middelgrunden, which has Cf=29%), and $Cf_{onshore\ wind}$ = 23%-29%.

Capacity factors of Wave Energy

Some numerical values can be found in the literature regarding the capacity factor of wave technologies, but their relevance should be discussed as no standard method was developed for evaluating this parameter (OES-IA, 2011). For instance, some developers define the rated power of a power plant as its peak power, whereas others determine it as the average power provided by the plant.

Capacity factors that derive from experimental data obtained during testing must be considered carefully. The analysis of the experimental data over a certain period of time must consider whether the ocean farm was operated continuously over the whole duration of the period considered or not. In addition, technologies might also be tested in experimental conditions that can differ significantly from their nominal conditions and hence distort the results, as well as their interpretation, if considered in the perspective of nominal conditions.

Hence, the context of the data must be borne in mind when analysing the capacity factor of ocean farms (wave and tidal energy farms) and comparing it to that of other technologies.

For wave technologies numerical values for the capacity factor as found in the literature range between 8% and 40%. The following numbers show the average capacity factors of some wave pilot plants as found in literature:

- Pico Oscillating Water Column: 8% (Le Crom, 2010)
- Pelamis: 25% to 40% (Pelamis, 2015)
- Wavestar: 16 to 34% (Marquis, Kramer, Kringelum, Fernández Chozas, & Helstrup Jensen, 2012)
- Wave Dragon: 23% to 35% (Tedd , Kofoed , Knapp, Friis-Madsen, & Sørensen, 2006)

In addition, the SI Ocean Project of the EC has set up a target of Cf_{wave}=25-30% for 2020 for wave and tidal technologies (Magagna, 2014).

Also, the international evaluation of the Levelised Cost of Energy of ocean technologies commissioned by the Ocean Energy Systems group of the International Energy Agency has defined the following capacity factors for wave technologies (Fernandez Chozas, MacGillivray, Raventos, Jeffrey, Nielsen, & Aderibigbe, 2015):

  - Second array: Cf_{wave} = 30%-35%
  - First commercial project: Cf_{wave} = 35%-40%

The Joint Research Centre of the European Commission has also provided its estimates on the average European capacity factors for wave technologies for years 2020 to 2050 (Magagna & Uihlein, 2015):

	Year 2020	Year 2030	Year 2040	Year 2050
Wave	2200 h/y	3000 h/y	3500 h/y	3500 h/y
	25%	35%	40%	40%

Projections for wave capacity factors according to the Danish Energy Authority (Energistyrelsen, 2012) for year 2030 are of 40%. Energinet.dk (Energinet.dk, 2011) estimates a capacity factor of 65% for year 2050.

In addition, the document developed by the Danish Partnership on Wave Energy sets a goal for wave energy in Denmark for year 2030-2035 of 30%-40% capacity factors (Nielsen, et al., 2012).

Capacity factors for solar PV in Denmark

The average Cf of solar PV is about 10% (Energinet.dk, 2014). Projections for solar PV capacity factors according to the Danish Energy Authority (Energistyrelsen, 2012) for year 2030 are of 14%. Instead, Energinet.dk (Energinet.dk, 2011) estimates a capacity factor for solar PV of 13% for year 2050.

V.II Results for the Quantitative Asssessment

This section presents the aggregated capacity credit of different mixes of RES for each of the four study periods, for each time span and calculated from two different approaches. A large number of results have been derived for the two set of analyses. Only the most illustrative ones are presented here. Firstly, results derived from an electricity-only system approach are presented. Then, these are compared with results based on an integrated energy system approach. “Annex VII. Further results on the Quantitative Assessment of the Capacity Credit of RES” provides a comprehensive overview of all the results derived for each scenario.

V.II.I Electricity-Only System Approach

The figures below show the capacity credit of each RES of the analysis and of the combination of all of them for various time spans in the ‘Combined RES Scenario’, calculated under an electricity-only system approach. Results for the *worst periods* are shown first, these are followed by the results of *peak demand periods*, then results for *Hi-RES periods* are shown, and lastly, *best periods* results are presented.

The bar diagrams (Figure 30 to Figure 33) indicate the production (in MW) of each RES of the analysis at each time span analysed, i.e. 1-hour, 3-hour, 6-hour, etc. The overall electricity demand (in MW) at that time span is also shown, as well as the electricity demand not covered by the RES at the time span of the study and/or the surplus or excess of electricity (in MW) due to higher production of RES compared to the electricity demand.

The tables accompanying the bar diagrams (Table 13 to Table 16) indicate the Capacity Credit of each RES of the study and of the combination of them at each time span. The Capacity Credit has to be read as the percentage of each RES installed capacity and of the total RES installed capacity available at that time span.

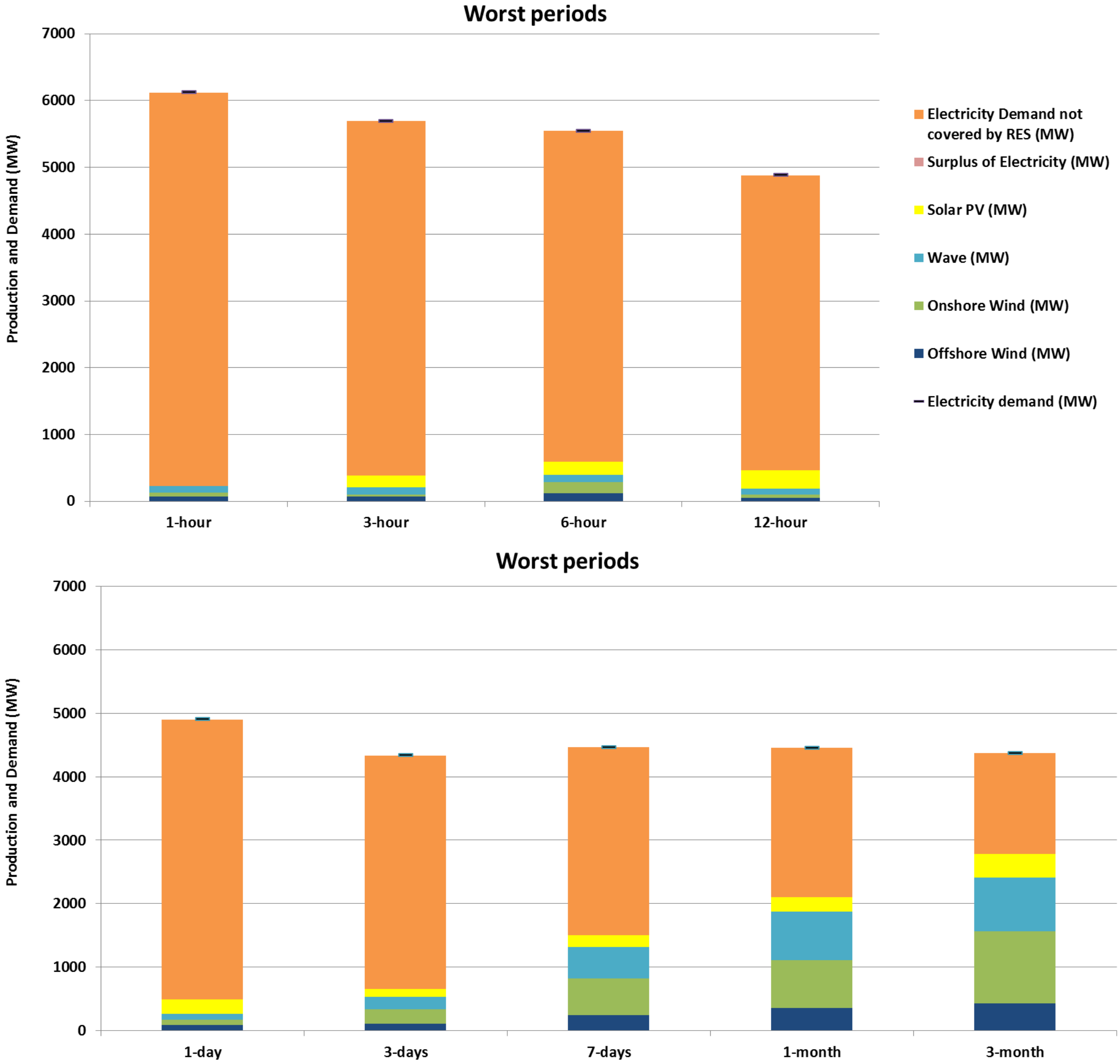
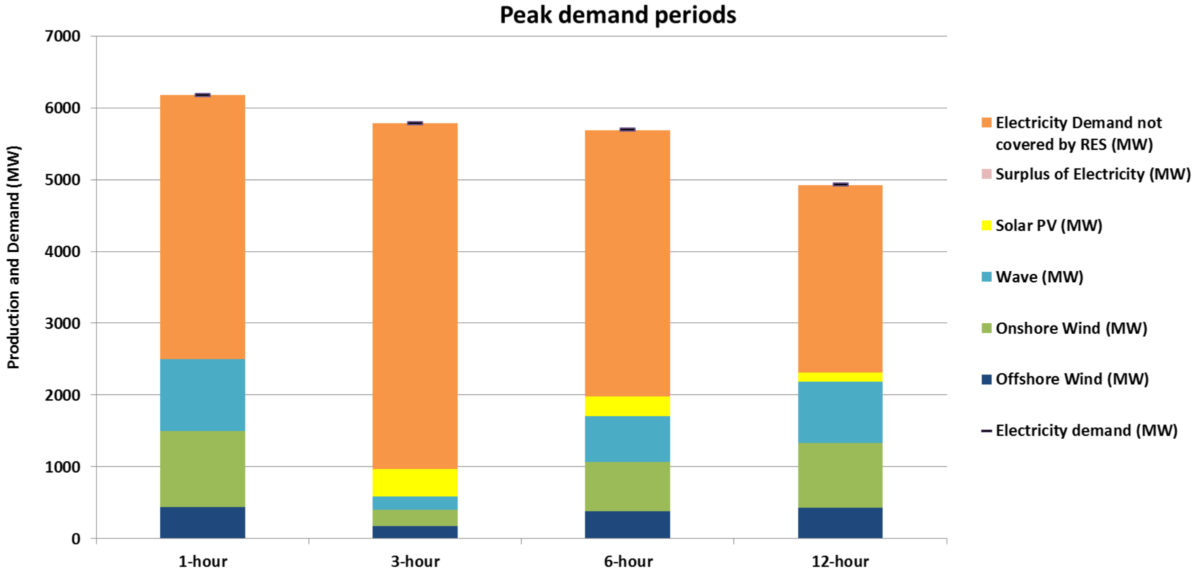


Figure 30. Production of each RES, overall electricity demand and electricity demand not covered by RES (all in MW) for *worst periods*, at various time spans, in the 'Combined RES Scenario', in an electricity-only system.

Table 13. Capacity Credit (expressed as a percentage of installed capacity) of each RES and of the combination of all of them for the *worst periods* and at various time spans in the 'Combined RES Scenario'. Date and hour when the time span occurs is also indicated. Electricity-only system aproach.

Capacity Credits (in % of Installed Capacity)						
Time span	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	24-jan, 17:00	2%	6%	1%	3%	0%
3-hour	24-jan, 15:00	3%	6%	1%	3%	3%
6-hour	25-jan, 06:00	4%	10%	4%	4%	4%
12-hour	24-jan, 12:00	3%	5%	1%	3%	5%
24-hour / 1-day	24-jan, 00:00	3%	8%	2%	3%	4%
72-hour / 3-day	15-feb, 00:00	5%	9%	5%	7%	2%
168-hour / 1-week	12-feb, 00:00	11%	21%	13%	17%	3%
1-month	February	15%	30%	17%	26%	4%
3-month (year quarter)	Jan-Feb-March	20%	37%	26%	29%	6%



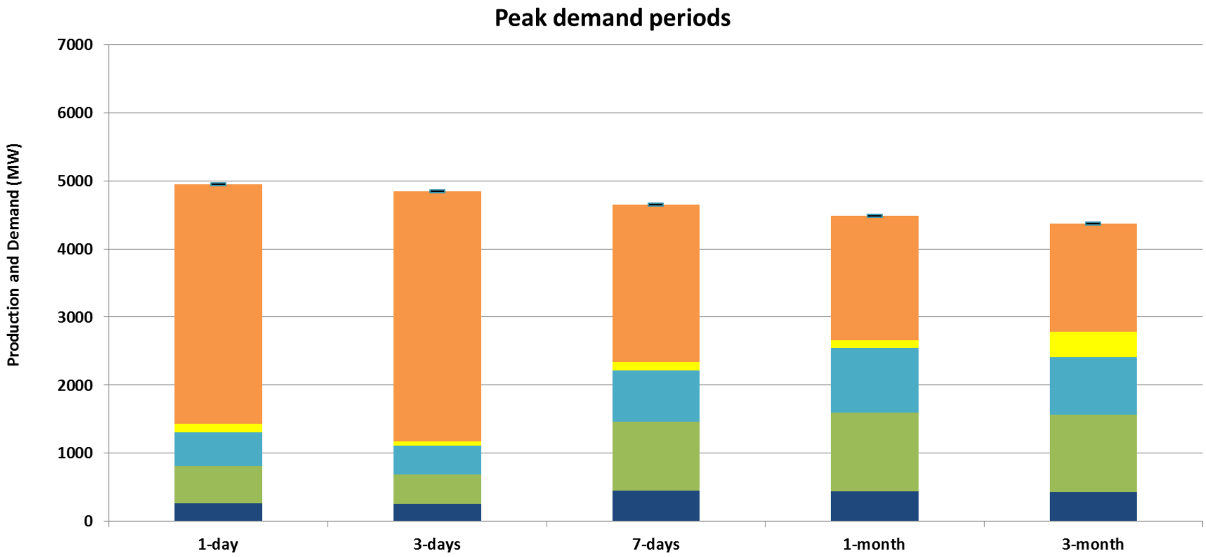


Figure 31. Production of each RES, overall electricity demand and electricity demand not covered by RES (all in MW) for *peak demand periods*, at various time spans, in the 'Combined RES Scenario', in an electricity-only system.

Table 14. Capacity Credit (expressed as a percentage of installed capacity) of each RES and of the combination of all of them for the *peak demand periods* and at various time spans in the 'Combined RES Scenario'. Date and hour when the time span occurs is also indicated. Electricity-only system aproach.

Capacity Credits (in % of Installed Capacity)						
Time span	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	25-jan, 17:00	18%	37%	24%	34%	0%
3-hour	25-jan, 09:00	7%	15%	5%	6%	7%
6-hour	25-jan, 12:00	14%	33%	16%	22%	5%
12-hour	25-jan, 12:00	16%	36%	21%	29%	2%
24-hour / 1-day	25-jan, 00:00	10%	23%	12%	17%	2%
72-hour / 3-day	16-jan, 00:00	8%	22%	10%	14%	1%
168-hour / 1-week	22-jan, 00:00	17%	38%	23%	26%	2%
1-month	January	19%	37%	26%	32%	2%
3-month (year quarter)	Jan-Feb-March	20%	37%	26%	29%	6%

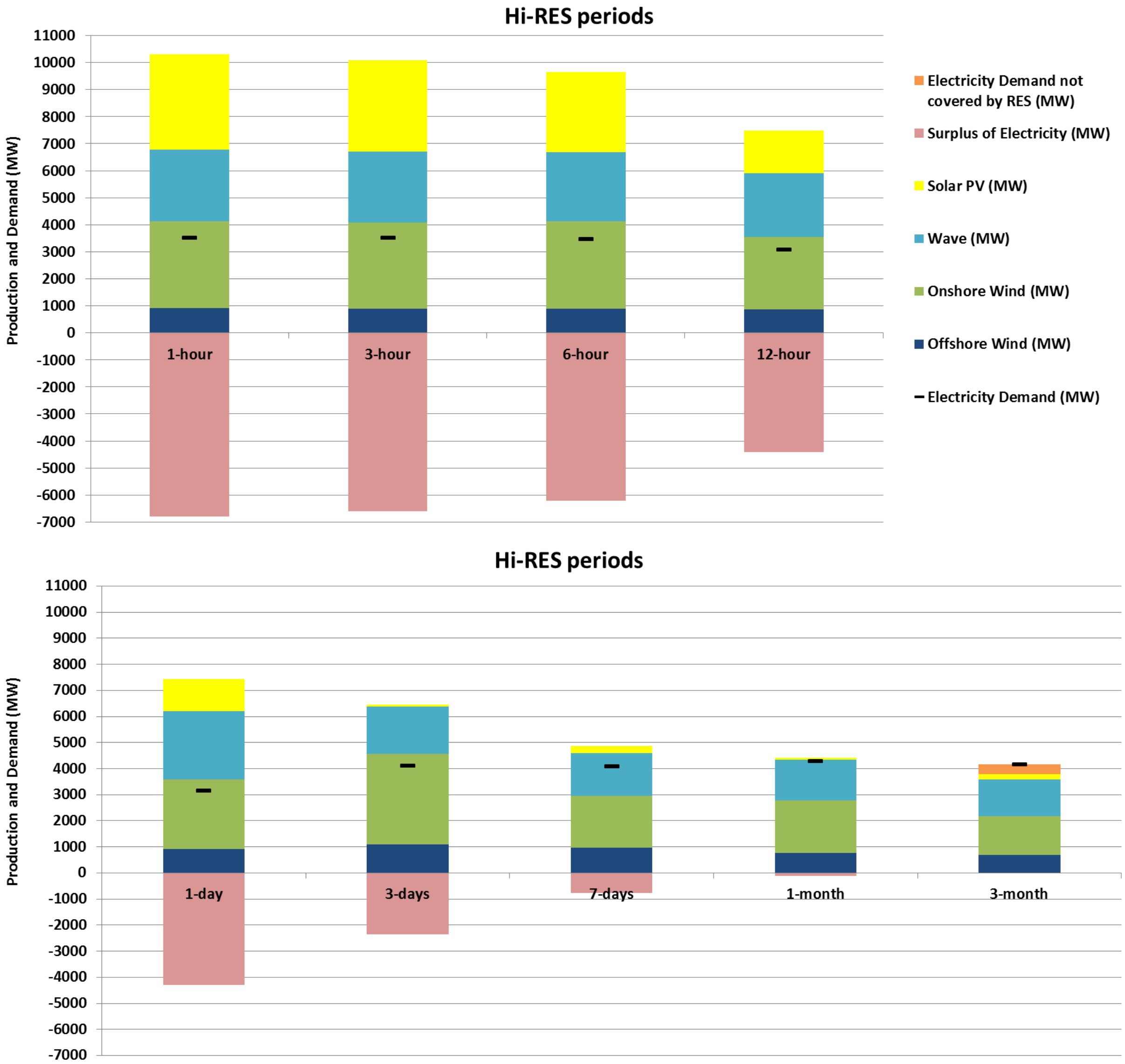
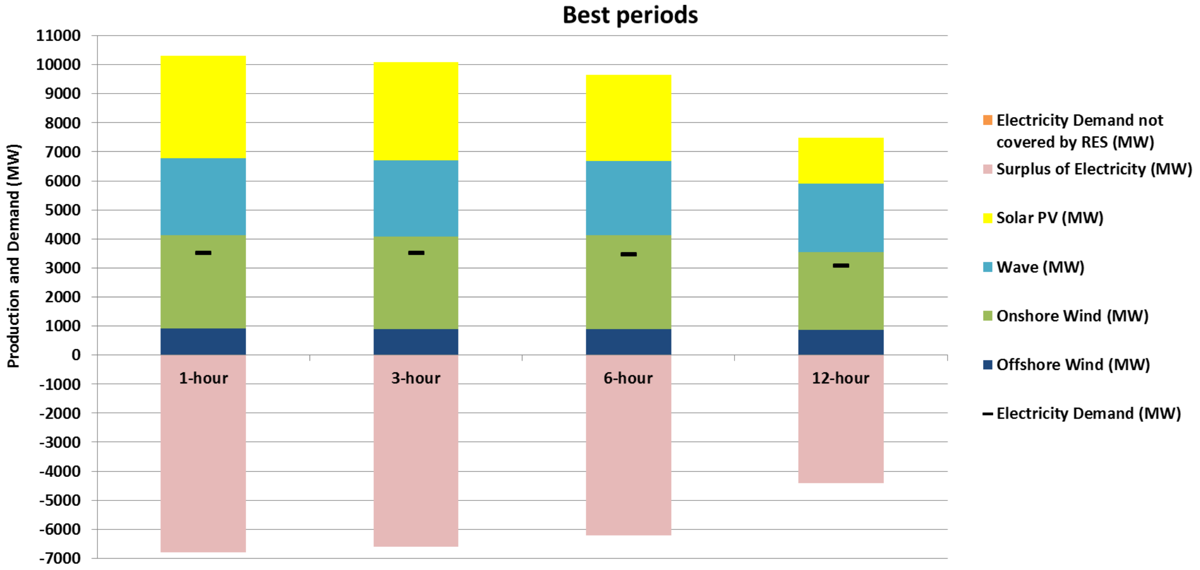


Figure 32. Production of each RES, overall electricity demand, electricity demand not covered by RES and surplus electricity (all in MW) for *Hi-RES periods*, at various time spans, in the 'Combined RES Scenario', in an electricity-only system.

Table 15. Capacity Credit (expressed as a percentage of installed capacity) of each RES and of the combination of all of them for the *Hi-RES periods* and at various time spans in the 'Combined RES Scenario'. Date and hour when the time span occurs is also indicated. Electricity-only system aproach.

Capacity Credits (in % of Installed Capacity)						
Time span	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	02-jun, 13:00	73%	78%	73%	91%	62%
3-hour	02-jun, 12:00	71%	76%	73%	90%	60%
6-hour	02-jun, 12:00	68%	77%	74%	88%	52%
12-hour	02-jun, 12:00	53%	73%	61%	81%	28%
24-hour / 1-day	02-jun, 00:00	53%	78%	61%	90%	22%
72-hour / 3-day	21-dec, 00:00	46%	94%	79%	62%	1%
168-hour / 1-week	22-okt, 00:00	34%	82%	46%	56%	5%
1-month	December	31%	65%	46%	53%	1%
3-month (year quarter)	Oct-Nov-Dec	27%	58%	34%	48%	3%



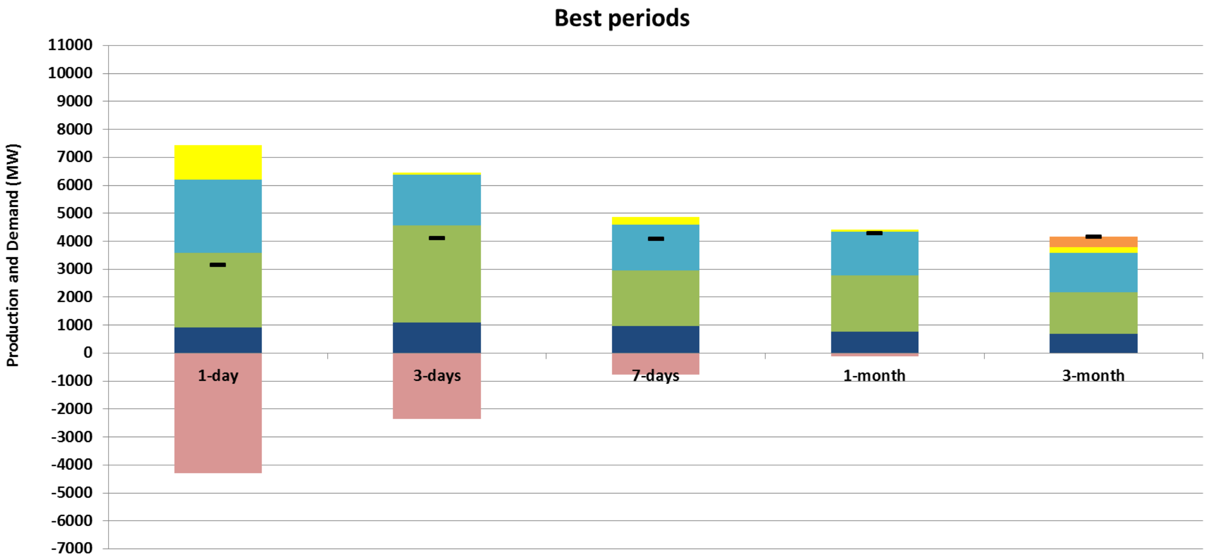


Figure 33. Production of each RES, overall electricity demand, electricity demand not covered by RES and surplus electricity (all in MW) for *Best periods*, at various time spans, in the 'Combined RES Scenario' in an electricity-only system.

Table 16. Capacity Credit (expressed as a percentage of installed capacity) of each RES and of the combination of all of them for the *Best periods* and at various time spans in the 'Combined RES Scenario'. Date and hour when the time span occurs is also indicated. Electricity-only system aproach.

Capacity Credits (in % of Installed Capacity)						
Time span	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	02-jun, 13:00	73%	78%	73%	91%	62%
3-hour	02-jun, 12:00	71%	76%	73%	90%	60%
6-hour	02-jun, 12:00	68%	77%	74%	88%	52%
12-hour	02-jun, 12:00	53%	73%	61%	81%	28%
24-hour / 1-day	02-jun, 00:00	53%	78%	61%	90%	22%
72-hour / 3-day	21-dec, 00:00	46%	94%	79%	62%	1%
168-hour / 1-week	22-okt, 00:00	34%	82%	46%	56%	5%
1-month	December	31%	65%	46%	53%	1%
3-month (year quarter)	Oct-Nov-Dec	27%	58%	34%	48%	3%

Table 17 provides a summary of the most important results of the analysis for an electrcitiy-only system. It shows the capacity credit in five scenarios with different mixes of RES (as indicated by the numbers in brackets, which show the annual production of offshore wind, onshore wind, wave and solar PV, respectively) for four study periods and for various time spans. Capacity credit results can be read as the percentage of the total RES installed capacity available in that study period and at that time span.

Table 17. Capacity credit of RES expressed as the percentage of the total RES installed capacity, calculated from an electricity-only system approach. Results for different periods and time spans are shown. Numbers in brackets show the annual production of offshore wind, onshore wind, wave and solar PV in the chosen scenario. Five scenarios are shown.

Electricity-only System Approach - Ambitious Offshore Wind Scenario [14.8 - 12.5 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	1% ≤ CC ≤ 3%	9% ≤ CC ≤ 30%	98% ≤ CC ≤ 99%	90% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 4%	17% ≤ CC ≤ 27%	89% ≤ CC ≤ 93%	82% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 16%	15% ≤ CC ≤ 29%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 31%	31% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Electricity-only System Approach - Ambitious Onshore Wind Scenario [10.7 - 16.6 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 28%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 94%
12-hour to 24-hour	2% ≤ CC ≤ 3%	15% ≤ CC ≤ 25%	89% ≤ CC ≤ 92%	81% ≤ CC ≤ 85%
3-day to 1-week	6% ≤ CC ≤ 15%	13% ≤ CC ≤ 27%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 21%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Electricity-only System Approach - Ambitious Wave Scenario [10.7 - 12.5 - 4 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	3% ≤ CC ≤ 3%	8% ≤ CC ≤ 30%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 4%	16% ≤ CC ≤ 27%	81% ≤ CC ≤ 87%	78% ≤ CC ≤ 82%
3-day to 1-week	7% ≤ CC ≤ 16%	14% ≤ CC ≤ 28%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Electricity-only System Approach - Ambitious Solar PV Scenario [10.7 - 12.5 - 0 - 4.2 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 19%	71% ≤ CC ≤ 77%	67% ≤ CC ≤ 77%
12-hour to 24-hour	2% ≤ CC ≤ 3%	11% ≤ CC ≤ 18%	60% ≤ CC ≤ 63%	56% ≤ CC ≤ 59%
3-day to 1-week	5% ≤ CC ≤ 12%	10% ≤ CC ≤ 20%	41% ≤ CC ≤ 57%	41% ≤ CC ≤ 57%
1-month to 3-month	16% ≤ CC ≤ 22%	21% ≤ CC ≤ 22%	30% ≤ CC ≤ 36%	30% ≤ CC ≤ 36%

Electricity-only System Approach - Combined RES Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 4%	7% ≤ CC ≤ 18%	68% ≤ CC ≤ 73%	68% ≤ CC ≤ 73%
12-hour to 24-hour	3% ≤ CC ≤ 3%	10% ≤ CC ≤ 16%	53% ≤ CC ≤ 53%	53% ≤ CC ≤ 53%
3-day to 1-week	5% ≤ CC ≤ 11%	8% ≤ CC ≤ 17%	34% ≤ CC ≤ 46%	34% ≤ CC ≤ 46%
1-month to 3-month	15% ≤ CC ≤ 20%	19% ≤ CC ≤ 20%	27% ≤ CC ≤ 31%	27% ≤ CC ≤ 31%

V.II.II Integrated Energy Systems Approach

The figures below show the capacity credit of each RES of the analysis and of the combination of all of them for various time spans in the 'Combined RES Scenario', calculated under an integrated energy system approach. Results for the *worst periods* are shown first, these are followed by the results of *peak demand periods*, then results for *Hi-RES periods* are shown, and lastly, *best periods* results are presented.

The bar diagrams (Figure 34 to Figure 37) indicate the production (in MW) of each RES of the analysis at each time span analysed, i.e. 1-hour, 3-hour, 6-hour, etc. The overall electricity demand (in MW) at that time span is also shown, as well as the electricity demand not covered by the RES at the time span of the study and/or the surplus or excess of electricity (in MW) due to higher production of RES compared to the electricity demand.

The tables accompanying the bar diagrams (Table 18 to Table 21) indicate the Capacity Credit of each RES of the study and of the combination of them at each time span. The Capacity Credit has to be read as the percentage of each RES installed capacity and of the total RES installed capacity available at that time span.

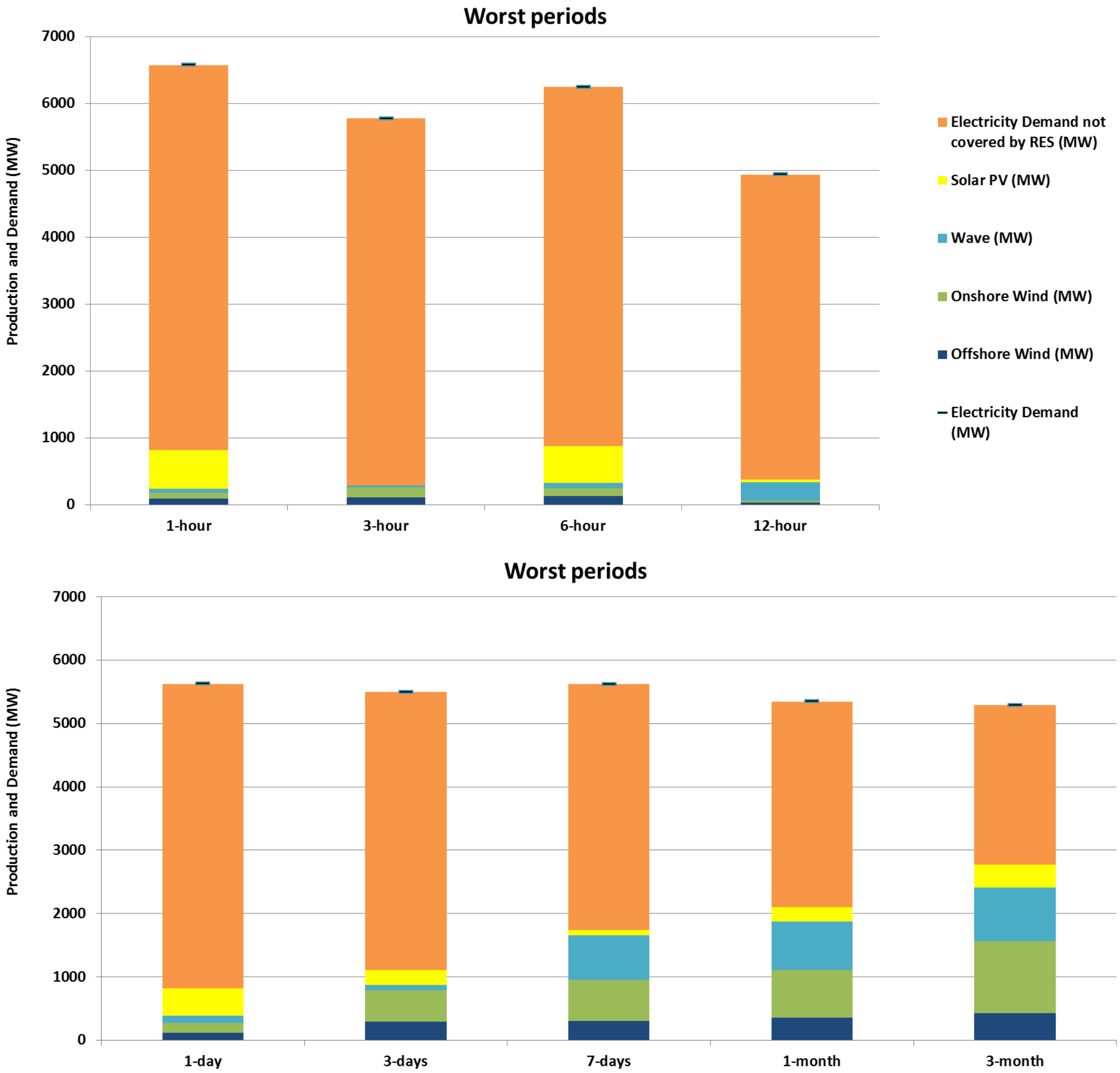
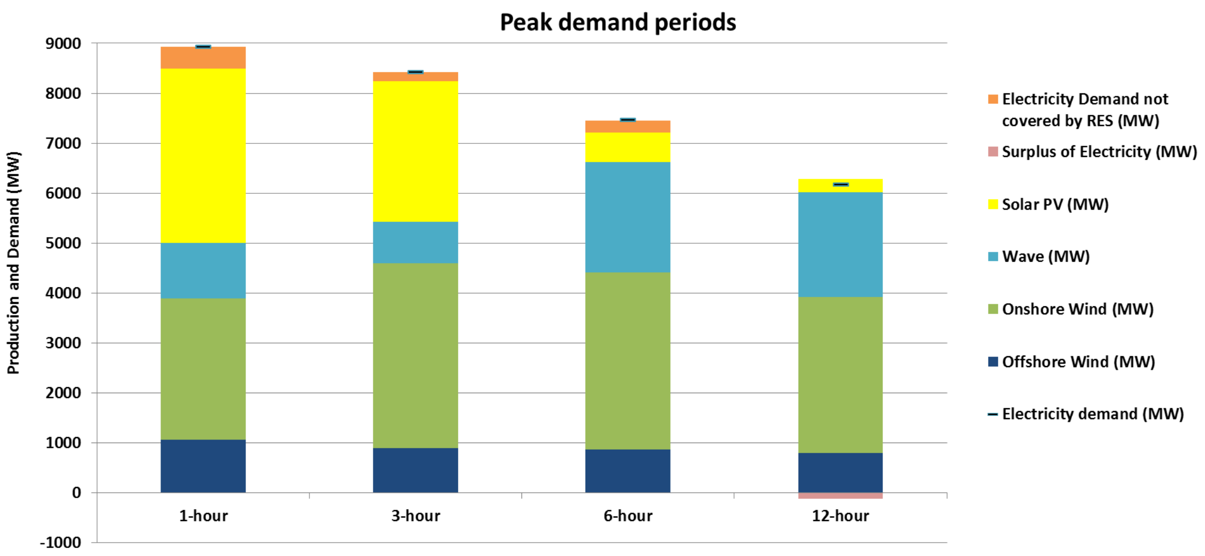


Figure 34. Production of each RES, overall electricity demand and electricity demand not covered by RES (all in MW) for *Worst periods*, at various time spans, in the 'Combined RES Scenario' in an integrated energy system.

Table 18. Capacity Credit (expressed as a percentage of installed capacity) of each RES and of the combination of all of them for the *Worst periods* and at various time spans in the 'Combined RES Scenario'. Date and hour when the time span occurs is also indicated. Integrated energy system aproach.

Capacity Credits (in % of Installed Capacity)						
Time span	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	26-feb, 09:00	6%	8%	2%	2%	13%
3-hour	21-feb, 18:00	2%	9%	3%	1%	0%
6-hour	26-feb, 06:00	7%	11%	3%	3%	12%
12-hour	08-jan, 12:00	3%	3%	1%	9%	1%
24-hour / 1-day	26-feb, 00:00	6%	10%	3%	4%	9%
72-hour / 3-day	21-feb, 00:00	8%	25%	11%	3%	5%
168-hour / 1-week	08-jan, 00:00	13%	26%	15%	24%	2%
1-month	February	16%	30%	17%	26%	5%
3-month (year quarter)	Jan-Feb-March	21%	37%	26%	29%	8%



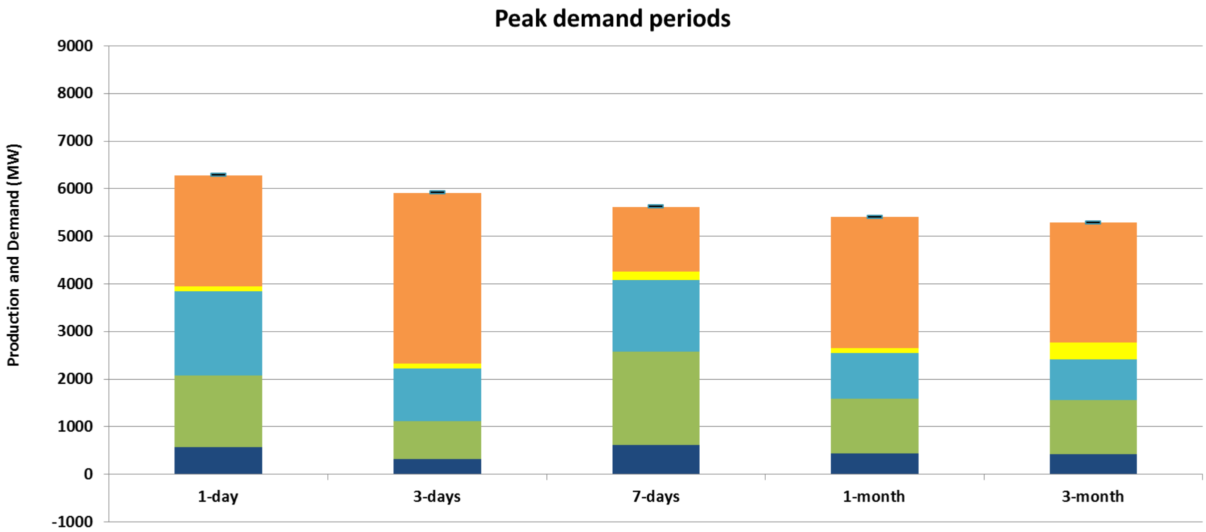


Figure 35. Production of each RES, overall electricity demand, electricity demand not covered by RES and surplus electricity (all in MW) for *peak demand periods*, at various time spans, in the 'Combined RES Scenario' in an integrated energy system.

Table 19. Capacity Credit (expressed as a percentage of installed capacity) of each RES and of the combination of all of them for the *peak demand periods* and at various time spans in the 'Combined RES Scenario'. Date and hour when the time span occurs is also indicated. Integrated energy system aproach.

Capacity Credits (in % of Installed Capacity)						
Time span	**Date & Hour**	**All RES Combined**	**Offshore wind**	**Onshore wind**	**Wave**	**PV Prod.**
1-hour	03-okt, 12:00	65%	91%	65%	38%	75%
3-hour	07-mar, 12:00	63%	76%	84%	28%	61%
6-hour	02-mar, 12:00	55%	73%	81%	75%	13%
12-hour	02-mar, 12:00	48%	68%	71%	71%	6%
24-hour / 1-day	10-jan, 00:00	30%	49%	34%	61%	2%
72-hour / 3-day	10-jan, 00:00	18%	28%	18%	38%	2%
168-hour / 1-week	29-jan, 00:00	33%	52%	45%	51%	4%
1-month	January	20%	37%	27%	32%	2%
3-month (year quarter)	Jan-Feb-March	21%	37%	26%	29%	8%

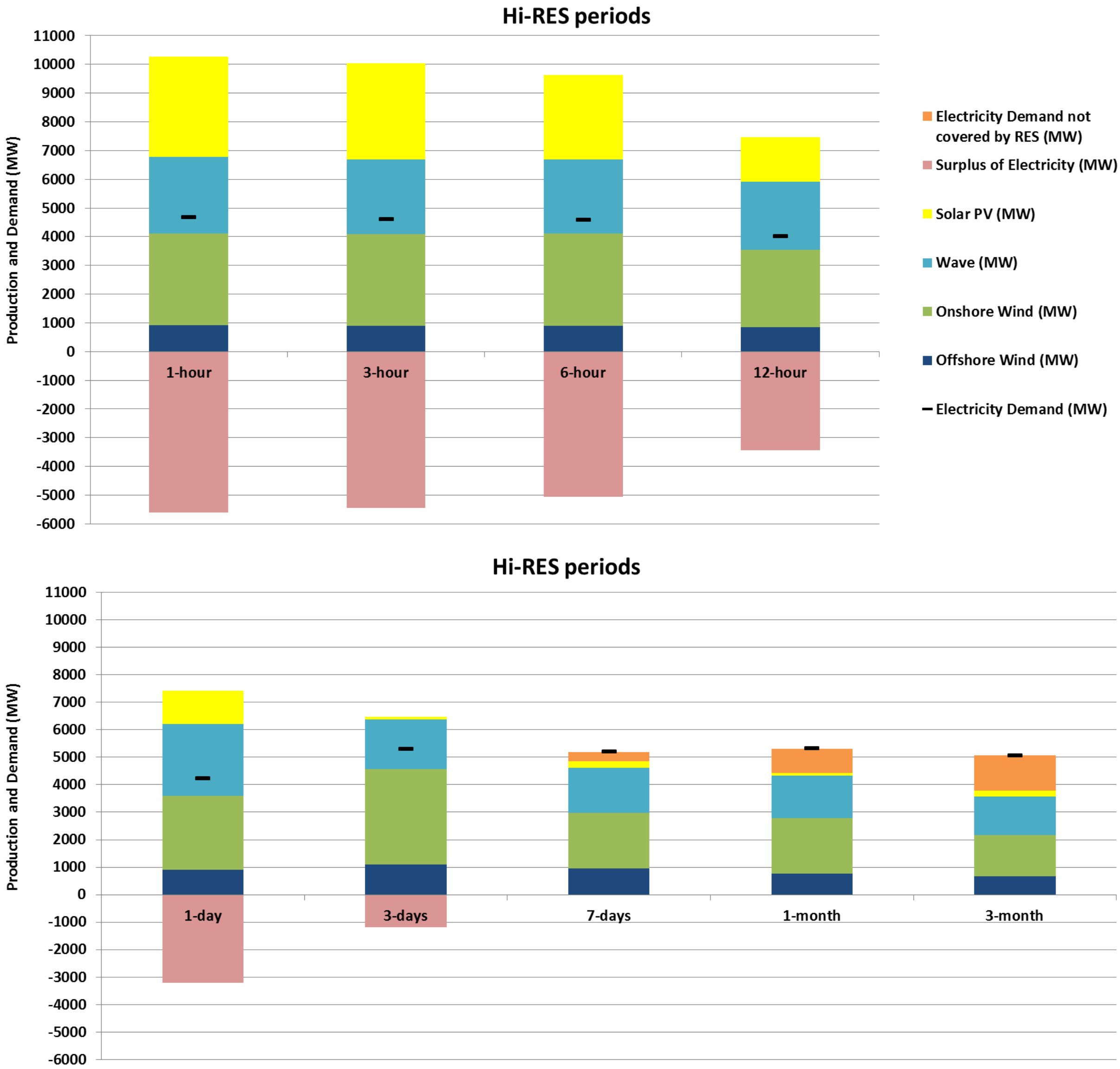


Figure 36. Production of each RES, overall electricity demand, electricity demand not covered by RES and surplus electricity (all in MW) for *Hi-RES periods*, at various time spans, in the 'Combined RES Scenario' in an integrated energy system.

Table 20. Capacity Credit (expressed as a percentage of installed capacity) of each RES and of the combination of all of them for the *Hi-RES periods* and at various time spans in the 'Combined RES Scenario'. Date and hour when the time span occurs is also indicated. Integrated energy system aproach.

Capacity Credits (in % of Installed Capacity)						
Time span	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	02-jun, 13:00	78%	78%	73%	91%	75%
3-hour	02-jun, 12:00	77%	76%	73%	89%	72%
6-hour	02-jun, 12:00	73%	76%	74%	88%	63%
12-hour	02-jun, 12:00	57%	73%	62%	81%	33%
24-hour / 1-day	02-jun, 00:00	57%	77%	61%	90%	26%
72-hour / 3-day	21-dec, 00:00	49%	93%	79%	62%	2%
168-hour / 1-week	22-okt, 00:00	37%	82%	46%	56%	5%
1-month	December	34%	65%	46%	53%	2%
3-month (year quarter)	Oct-Nov-Dec	29%	58%	34%	48%	4%

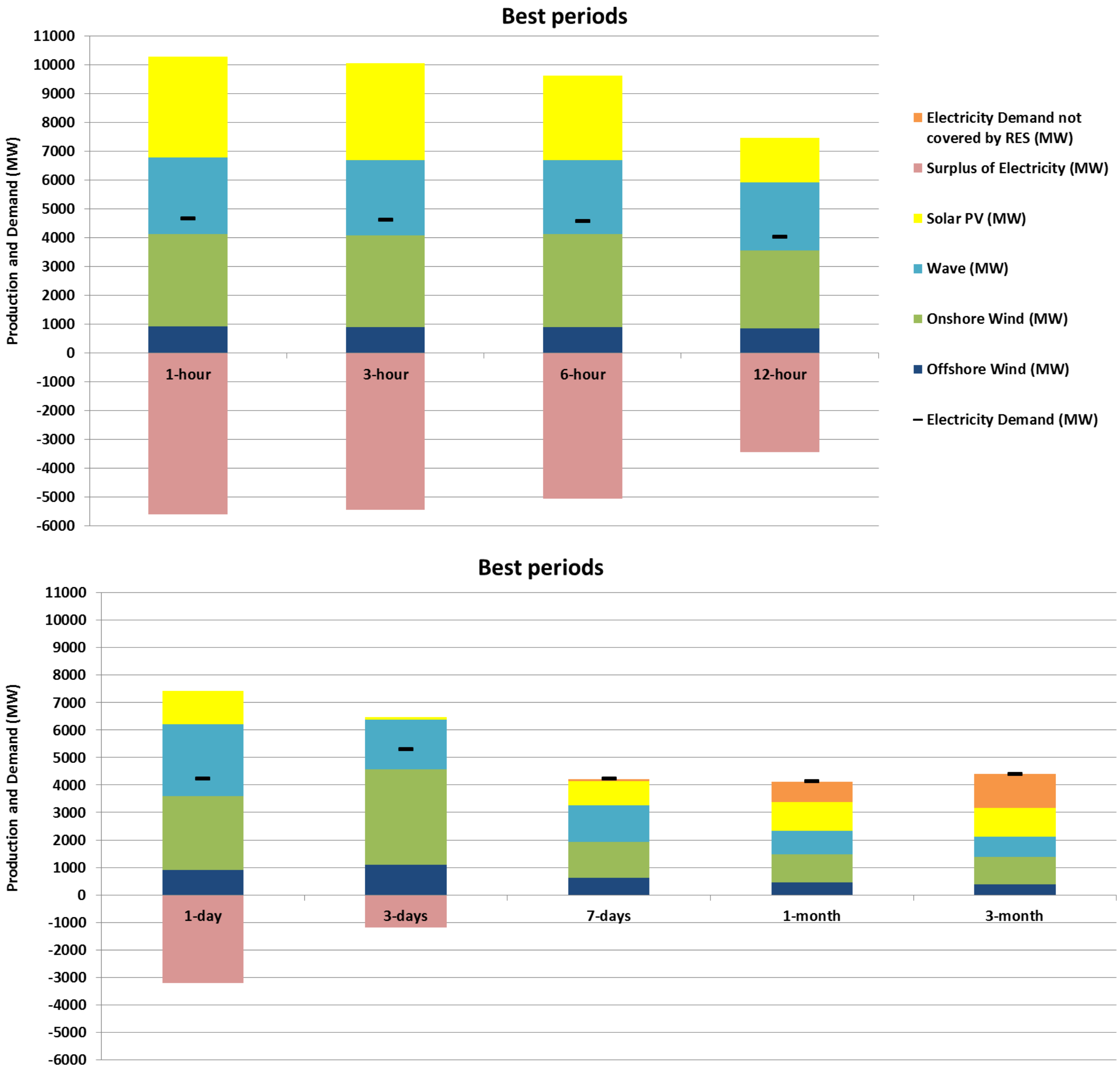


Figure 37. Production of each RES, overall electricity demand, electricity demand not covered by RES and surplus electricity (all in MW) for *best periods,* at various time spans, in the 'Combined RES Scenario' in an integrated energy system.

Table 21. Capacity Credit (expressed as a percentage of installed capacity) of each RES and of the combination of all of them for the *best periods* and at various time spans in the 'Combined RES Scenario'. Date and hour when the time span occurs is also indicated. Integrated energy system aproach.

Capacity Credits (in % of Installed Capacity)						
Time span	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	02-jun, 13:00	78%	78%	73%	91%	75%
3-hour	02-jun, 12:00	77%	76%	73%	89%	72%
6-hour	02-jun, 12:00	73%	76%	74%	88%	63%
12-hour	02-jun, 12:00	57%	73%	62%	81%	33%
24-hour / 1-day	02-jun, 00:00	57%	77%	61%	90%	26%
72-hour / 3-day	21-dec, 00:00	49%	93%	79%	62%	2%
168-hour / 1-week	13-aug, 00:00	32%	53%	30%	46%	19%
1-month	June	26%	40%	23%	29%	23%
3-month (year quarter)	April-May-June	24%	33%	23%	26%	22%

Table 22 shows the capacity credit in five scenarios with different mixes of RES (as indicated by the numbers in brackets, which show the annual production of offshore wind, onshore wind, wave and solar PV, respectively) for four study periods and for various time spans. Capacity credit results can be read as the percentage of the total RES installed capacity available in that period and at that time span. Results are derived with EnergyPLAN energy system's model using a technical strategy that optimises, i.e. minimises, fuel consumption, and adjusts demands according to what is possible with the installed technologies.

Table 22. Capacity credit of RES expressed as the percentage of the total RES installed capacity, calculated from an integrated energy system approach. Results for different periods and time spans are shown. Numbers in brackets show the annual production of offshore wind, onshore wind, wave and solar PV in the chosen scenario. Five scenarios are shown.

Integrated Energy System Approach - Ambitious Offshore Wind Scenario [14.8 - 12.5 - 0 - 0 TWh/y]

	Worst periods	Peak demand periods	Hi-RES periods	Best periods
1-hour to 6-hour	4% ≤ CC ≤ 6%	77% ≤ CC ≤ 91%	98% ≤ CC ≤ 99%	90% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 3%	40% ≤ CC ≤ 59%	89% ≤ CC ≤ 93%	87% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 22%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Integrated Energy System Approach - Ambitious Onshore Wind Scenario [10.7 - 16.6 - 0 - 0 TWh/y]

	Worst periods	Peak demand periods	Hi-RES periods	Best periods
1-hour to 6-hour	3% ≤ CC ≤ 5%	75% ≤ CC ≤ 90%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 94%
12-hour to 24-hour	2% ≤ CC ≤ 3%	38% ≤ CC ≤ 55%	89% ≤ CC ≤ 92%	86% ≤ CC ≤ 92%
3-day to 1-week	6% ≤ CC ≤ 18%	18% ≤ CC ≤ 21%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 29%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Integrated Energy System Approach - Ambitious Wave Scenario [10.7 - 12.5 - 4 - 0 TWh/y]

	Worst periods	Peak demand periods	Hi-RES periods	Best periods
1-hour to 6-hour	3% ≤ CC ≤ 5%	75% ≤ CC ≤ 79%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 5%	42% ≤ CC ≤ 70%	81% ≤ CC ≤ 88%	78% ≤ CC ≤ 88%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 24%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 30%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Integrated Energy System Approach - Ambitious Solar PV Scenario [10.7 - 12.5 - 0 - 4.2 TWh/y]

	Worst periods	Peak demand periods	Hi-RES periods	Best periods
1-hour to 6-hour	2% ≤ CC ≤ 7%	60% ≤ CC ≤ 71%	75% ≤ CC ≤ 82%	71% ≤ CC ≤ 82%
12-hour to 24-hour	1% ≤ CC ≤ 4%	49% ≤ CC ≤ 52%	64% ≤ CC ≤ 67%	59% ≤ CC ≤ 63%
3-day to 1-week	8% ≤ CC ≤ 14%	14% ≤ CC ≤ 16%	44% ≤ CC ≤ 61%	44% ≤ CC ≤ 61%
1-month to 3-month	17% ≤ CC ≤ 23%	22% ≤ CC ≤ 23%	32% ≤ CC ≤ 38%	32% ≤ CC ≤ 38%

Integrated Energy System Approach - Combined RES Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]

	Worst periods	Peak demand periods	Hi-RES periods	Best periods
1-hour to 6-hour	2% ≤ CC ≤ 7%	55% ≤ CC ≤ 65%	73% ≤ CC ≤ 78%	73% ≤ CC ≤ 78%
12-hour to 24-hour	3% ≤ CC ≤ 6%	30% ≤ CC ≤ 48%	57% ≤ CC ≤ 57%	57% ≤ CC ≤ 57%
3-day to 1-week	8% ≤ CC ≤ 13%	18% ≤ CC ≤ 33%	37% ≤ CC ≤ 49%	32% ≤ CC ≤ 49%
1-month to 3-month	16% ≤ CC ≤ 21%	20% ≤ CC ≤ 21%	29% ≤ CC ≤ 34%	24% ≤ CC ≤ 26%

V.III Discussion of Results

This section provides a discussion of the set of results presented above.

V.III.I Discussion on the Qualitative Assessment

Results of the qualitative assessment have supported the benefits of a mix of the four RES of the study with comparison to an offshore and onshore wind dominated RE mix for Denmark.

The average delay between waves and winds of 1 to 4 hours and the low correlation between solar PV production and wave or wind production, benefits a RES generation mix with the four RES of the study. This is also supported by the higher correlation of solar PV and onshore wind with the classical electricity demand when these two RES are combined, in comparison to a portfolio where only one RES is available.

The analysis of null production hours for different RES scenarios also shows that a RES mix including wave and solar PV besides wind energy is also positive. When the four RES of the study are combined the hours with no production reduce to zero, i.e. there is RES production all hours during the study year. This is, when wave and/or solar PV are added to the mix of offshore and onshore wind, the number of hours with low production decreases; and this is maximised when the four RES are combined together.

A discussion is provided below with regards to the Capacity factors assumed in this study. This is due to the fact that Energinet.dk (Energinet.dk, 2011) and the Danish Energy Authority (Energistyrelsen, 2012) (Energistyrelsen, 2014) project an improvement of wind and wave harnessing technologies; and as such, their capacity factors are indeed expected to increase significantly.

This is however not the case for solar PV. The capacity factor of solar PV might increase by 1% or 2% maximum, whereas a 5% to 10% increase is expected for offshore wind and wave technologies. Nevertheless there is higher uncertainty in the development of wave energy converters, and that justifies why capacity factors' estimates vary depending on the source.

These improvements in technologies capabilities provide a different scenario as the one analysed in this project. As examined here, the capacity factor affects directly on the capacity credit of RES. Thus, an improvement on RES capacity factors is expected to lead to higher capacity credits.

Background values of this report are year 2013 Danish average capacity factors:

- $Cf_{offshore\ wind} = 40\%$
- $Cf_{onshore\ wind} = 25\%$
- $Cf_{wave} = 32\%$
- $Cf_{solar\ PV} = 11\%$

Where: $Cf_{offshore\ wind} > Cf_{wave} > Cf_{onshore\ wind} > Cf_{solar\ PV}$

According to Energinet.dk projections (Energinet.dk, 2011) the following average capacity factors might be true in year 2050:

- $Cf_{offshore\ wind} = 44\%$
- $Cf_{onshore\ wind} = 28\%$

- $Cf_{wave} = 65\%$
- $Cf_{solar\ PV} = 13\%$

Where: $Cf_{wave} > Cf_{offshore\ wind} > Cf_{onshore\ wind} > Cf_{solar\ PV}$

Wave energy technologies are expected to greatly develop in the coming years (Energinet.dk, 2011) and also to be installed further offshore, covering deeper waters of the Danish North Sea. The most optimistic average power productions of wave energy reveal capacity factors higher than for offshore wind. If wave energy proves to have a higher or equal capacity factor than offshore wind, the picture of the aggregated capacity credit of RES can change positively.

Overall, RES technological developments, and thus, increased capacity factors, will come along with higher contribution of RES to security of supply.

V.III.II Discussion on the Quantitative Assessment

How *worst periods, peak-demand periods, hi-RES periods* and *best periods* influence on the CC_{RESmix}:

- CC_{RESmix} in *worst* and *peak-demand periods*, and in *hi-RES* and *best periods*, respectively, follow the same trend. Minimum CC_{RESmix} appear for *worst* and *peak-demand periods*, and maximum CC_{RESmix} appear in *hi-RES* and *best periods.*

- *Worst periods*, which represent hours of maximum electricity demand and minimum RES production, show the hours where production of RES is minimal. Thus, the minimum CC_{RESmix} is derived, it being in the order of 1% of total RES installed capacity. This value increases to 4% when a time-span of 24-hour is chosen. *Peak-demand periods* show a CC_{RESmix} varying from 7% and 17% for 1-hour to 24-hour time spans, respectively.

- In *hi-RES periods and best periods*, i.e. hours of maximum RES production and minimum electricity demand, CC_{RESmix} can be as high as 99%.

- *Worst periods*, *hi-RES periods and best periods* sometimes occur in the same month of the year, in December month. *Worst periods* are mostly in January and also in February, sometimes in December too; p*eak-demand periods* are generally in January; *hi-RES periods* are generally in June, sometimes also in December; and *best periods* are generally in March, June and December months.

- Contrary to the traditional methodology utilised to derive CC values of RES, *worst hours* show less contribution from RES than in *peak-demand hours*. Thus, CC_{RESmix} in w*orst hours* are generally lower than in *peak-demand hours*.

How the time spans (1-hour, 3-hour, 12-hour, 24-hour, 3-day, etc.) influence on the CC_{RESmix}:

- There are significant differences among the capacity credits of the RES mix (CC_{RESmix}) throughout the studied time spans, i.e. on an hourly and intra-day basis, on a daily and intra-week basis and on a monthly basis.

- Generally, the CC of RES on an intra-day basis and on a daily basis differs in about 10 points, and the same trend appears when comparing the CC occurs when comparing the CC of RES on a daily basis and on a monthly basis. Therefore, the time span selected to calculate the CC_{RESmix} can have strong impact on the CC value CC used in the planning of the electricity system. These results invite to consider different timescales when evaluating the CC of RES, and to differentiate among a 'worst CC', 'reasonable worst CC', 'reasonable good CC' and 'best CC' for a given system, for example.

- The comparison between the 1-hour and the 24-hour time spans illustrates the difference between today's electricity system and future systems. Today's system is represented by the 1-hour condition, where demand does not follow production and peak hours are frequent. The future system is represented by the 24-hour averaged condition, where electricity consumption (loads) can be shifted throughout the day (in 12 to 24-hour periods) to hours where electricity demand is lower or RES production is higher, decreasing the stress over the system. By doing that: i) peaks in electricity consumption could be reduced, ii) 1-hour, 3-hour and 6-hour time spans would disappear, iii) and overall, as shown in the tables, CC_{RESmix} would increase. In other words, if peak demand hours were eliminated, the electricity consumption would respond to a more average and flat pattern, and there would be less demand peaks throughout the year. As a direct effect of this, the 1-hour to 6-hour time spans would disappear, and maybe also the 12-hour time span; and the contribution that RES could make to the system (the CC_{RESmix}) would be dictated by the value derived for the 24-hour time span.

How the RES mix, i.e. the scenarios of the analyses, influence on the CC_{RESmix}:

- Generally, CC_{RESmix} values are of the same range and follow the same trends for every scenario of the analysis.

- As a general trend $CC_{Offshore\ wind} > CC_{Wave} > CC_{Onshore\ wind} > CC_{Solar\ PV}$; and the CC of a RES mix is proportional to this relationship, it increases or decreases accordingly to the contribution of each RES in the mix. For example, increasing the amount of offshore wind or wave in a scenario increases the CC_{RESmix} more than if solar PV was added to that scenario. This can be seen by comparing the 'Ambitious Offshore Wind' or 'Ambitious Wave' scenarios with the 'Ambitious Solar PV' or 'Combined RES' scenarios.

- As in the current Danish system, which has significant offshore wind and onshore wind installed capacity, adding wave to the system would keep constant or increasing the CC_{RESmix}, and adding solar PV to the system would decrease the CC_{RESmix}.

How the approach (electricity-only or integrated energy system) influences on the CC_{RESmix}:

It is of much interest to investigate if the capacity credit of the renewable energy portfolio of focus changes when modelling it within an electricity-only system or in an integrated energy system.

The biggest difference when modelling an electricity-only system or an integrated energy system is in the capacity credit of *peak-demand periods*. Particularly, for the capacity credits within the intra-daily time-scale, i.e. in the interval 1-hour to 24-hour. In these time spans, the capacity credit of the RES portfolio increases, reaching almost the capacity credits of the *hi-RES periods*. The raise is highest for the smallest time span (i.e. 1-hour) and it is less pronounce as the time span increases. However, CC_{RESmix} improves only slightly for the w*orst periods* in the 1-hour to 24-hour time spans. This can be explained by the fact that in *worst periods* RES production is minimum, and therefore there is no opportunity in the system to transfer the electricity production from RES to other hours. In an integrated system it will be possible to (and indeed EnergyPLAN model does so) shift peak-demand hours to hours where RES production is high, and the direct results of that approach can be seen here. By implementing an integrated energy system approach, the CC of RES in *peak-demand periods* increases significantly and it almost reaches the values achieved in *hi-RES periods* and *best periods.*

For daily, weekly and monthly time spans, the CC_{RESmix} does not change significantly if modelling an electricity-only system or an integrated energy system. This can be explained by the fact that integrated energy systems have a smoothing effect with regards to the integration of RES on the intra-day timescale.

In those scenarios where there is significant solar PV installed, the CC_{RESmix} in all time spans increases when an integrated energy system approach is used. In other words, when the RES portfolio includes a high percentage of solar PV production (10% to 20% of total RES production), the contribution of RES in *periods of peak-demand* and in *worst periods* proves to be higher if an integrated energy system approach is used.

The comparison in numbers among CC values achieved with an electricity-only system approach and an integrated energy system approach are the following:

- Minimum, maximum and average CC_{RESmix} values depend on the periods considered: worst periods, peak-demand periods, hi-RES periods or best periods.

- In an electricity-only system, the minimum aggregated contribution that RES can have in *worst periods* is 1% to 3% and occurs for the 1-hour time span. Also in worst periods but for 3-month time spans, CC_{RESmix} increases to 20%-31%. Also for the worst periods, these numbers increase slightly in an integrated energy system, rising to 2% to 4% for the 1-hour time span.

- Peak periods do not coincide with minimum CC values. In an electricity-only system the CC during *peak-demand periods* range 7%-9% for the 1-hour interval to 16%-27% in the 24-hour interval. Numbers do change significantly in an integrated energy system and increase to 55%-77% for the 1-hour interval to 48%-70% in the 24-hour interval.

- Maximum contributions that RES can have happens on *best periods* and for the 1-hour time, and are up to 70-80-99% depending on the RES mix. As expected values lower a bit in an integrated energy system.

- The average contribution that can be expected from RES in worst and peak demand hours on a monthly average varies in the range 15% - 31%, depending on the scenario (the more offshore wind and wave installed in the system, the higher the CC, and the opposite is true for onshore wind and solar PV). This is true in both an electricity-only and in an integrated energy system. The average CC_{RESmix} is close to the average capacity factor of the RES mix during the period of consideration, which is line with (Gross, et al., 2007), who state that the CC of a RES mix can at most equal the Cf of the RES mix.

- If the daily average is considered instead, the overall average CC_{RESmix} in worst and peak demand hours varies in the range 3% - 27%, depending on the scenario, in an electricity-only system; and 3% - 70% in an integrated energy system. Here, the positive effects of an integrated energy system can be clearly seen. Integrated energy systems need however to be further developed, where components from all sectors will be able to contribute to the system electrical balance and hence increase the CC of the mix of RES (Mathiesen, 2009).

Chapter VI – Conclusions

VI.I Conclusions in a Nutshell

Two major conclusions arise from this project. The first one is related to the renewable energy mix that Denmark has chosen for coming years, and the second one relates to the capacity credit of RES.

Denmark has set ambitious goals in the energy sector and by 2035 it aims to be independent of fossil fuels in the heat and electricity sector. In order to achieve 2035 goals, offshore and onshore wind generation are meant to increase significantly, and only small amounts of solar PV and almost none wave power are envisioned in the renewable energy mix. Therefore, Denmark has chosen a wind-dominated renewable energy system for the future.

The project has explored the relationships among the three renewable energy sources and what they individually and in synergy can provide to the electricity system. For this, the correlation between RE production and demand, the correlation between wind, waves and solar PV, and the number of hours per year of null-, minimum- and full-production of different RE mixes, have been examined.

Results of the project show the following findings:

vii) Onshore wind and solar PV are the RES higher correlated to the classical electricity demand, with a cross-correlation factor of 0.14 and 0.13, respectively.

viii) Among the scenarios studied including offshore and onshore wind, the highest cross-correlation factor between RE production and demand is achieved by combining offshore wind, onshore wind, wave and solar PV; and the cross-correlation factor is of 0.17. These numbers can be compared with the cross-correlation factor of RE production and demand in year 2013, of 0.13.

ix) There is high correlation between wind and wave power production, which is explained by the fact that waves are created by winds; cross-correlation factors are between 0.6 and 0.7 for a zero-hour time lag. However, and interesting property is that there is also an average delay between wind and wave production, which lies in between 1 to 2 hours for offshore wind production, and 1 to 4 hours for onshore wind production.

x) Solar PV is low correlated with offshore wind, onshore wind or wave production, presenting a low negative correlation.

xi) Among the scenarios analysed, the renewable energy mix that combines offshore wind, onshore wind, wave and solar PV is the one that reduces to a minimum the number of hours per year with a production below 1% of total production, and the number of hours per year with a production below 5% of total production, with numbers of 190 h/y and 2070 h/y, respectively. The combined offshore and onshore wind energy system presents numbers of 519 h/y and 2786 h/y, respectively.

xii) An interesting finding, which relates to the second set of conclusions to be presented below, is that the number of hours per year with no production from RES is as low as 0 h/y in most of all the RES scenarios analysed including the four RES of the study.

As a result, the first set of findings of the project highlight that there are stronger benefits in a Danish diversified renewable energy mix based on wind, wave and solar PV, than in the wind-dominated renewable energy system that Denmark is aiming for.

The second set of conclusions is related to the capacity credit of RES in the Danish system, and the contribution that RES can provide to security of supply.

In system adequacy assessments the contribution that RES can make to security of supply is evaluated by the capacity credit parameter. However, the traditional general assumption in adequacy forecasts is that variable renewable generation cannot contribute to system adequacy, and thus, that the capacity credit of RES is equal to zero. This project has aimed to go beyond this assumption and has investigated different methods to evaluate the contribution that RES can provide to the Danish system.

Accordingly, the capacity credits of different future 2030 Danish scenarios including offshore wind, onshore wind, wave and solar PV have been examined. Results of the project have proved that RES do have a positive capacity credit, with a value above zero.

Results obtained in the project based on a new approach show that the contribution to security of supply that can be expected from RES averaged over a month in the worst month and in the peak-demand month of the year is in the range of 15% to 30% of RES's installed capacity. The interval 15% to 30% depends on the scenario, as the more offshore wind and wave installed in the system, the higher the capacity credit of the RES mix. The opposite is true for onshore wind and solar PV, being solar PV the RES that presents lower capacity credits.

According to the scenarios analysed, a capacity credit of 15%-30% indicates that in a monthly average between 2000 MW and 3000 MW are available in the worst month (February in this analysis) and in the peak-demand month (January in this analysis) to cover the electricity demand. This finding applies both when considering an electricity-only system and an integrated energy system. And again, the intervals depend on the scenario considered.

If the daily averages are considered instead, the average capacity credit of the RE mix in the worst day of the year (when demand is maximum and RES production is minimum) is of 3%-4% of RES installed capacity. This corresponds to 300MW-400MW, and applies both when considering an electricity-only system and an integrated energy system.

By contrast, the average capacity credit of the RE mix in the peak-demand day of the year (when demand is maximum) changes significantly when considering an electricity-only or an integrated energy system. In the former system, the capacity credit varies in the range 16% to 27% (around 2500 MW), whereas in the latter system it presents a value of 50% to 70% of the RES installed capacity (between 5500 MW and 7000 MW). This shows the positive effects towards integrating RES of integrated energy systems, where the electricity, heating and transport sectors are merged, and of flexible electricity demand.

In addition, the Danish TSO and the Danish Energy Authority project an improvement of wind and wave harnessing technologies, and accordingly, their capacity factors are expected to increase significantly. This is especially true for wave technologies, which in some scenarios are projected to have capacity factors higher than offshore wind. These improvements provide a different scenario as the one analysed in this project, with the result that the aggregated capacity credit of RES will change positively.

Overall, this project has proved that RES can contribute to security of supply in the periods of more risk to the system, i.e. in worst periods and in the peak-demand periods. And as RE technology developments happen, RES will be capable of contributing more to system adequacy.

VI.II Recommendations for the TSO

A set of recommendations on how to evaluate the contribution that RES can make to security of supply, i.e. on the evaluation of the parameter CC_{RESmix}, are provided below. These recommendations aim to go beyond the traditional approach used in adequacy forecasts to meet security of supply.

The methodology traditionally used by TSOs, the ENTSO-E and the IEA to calculate the capacity credit of RES analyses the production of the RE mix of focus during the 10^{th} to 100^{th} highest consumption hours during a year. This approach is not suitable when RES are part of the electricity generation mix.

Accordingly, this project has developed a methodology that looks into the capacity credit of a RES mix in a new way. It investigates the capacity credit of a mix of RES at different time spans (intraday, intraweek, intermonth and seasonally), at key time periods during a year (in worst periods, in peak-demand periods, in high RES periods and in best periods), and considering two very different energy systems (an electricity-only system and an integrated energy system), and demand responses (flexible and inflexible electricity demand).

The following recommendations shall be taken as part of a new methodology:

- Investigate RES production throughout key time periods during a year, and not only during a given number of highest consumption hours of a year. This study has examined RES power production in periods of peak-demand, in periods where RES production is minimum and demand is maximum, in periods where RES production is maximum, and in periods where RES production is maximum and demand is minimum. Each of the four periods analysed present its own challenges, and therefore it is relevant to address all of them from a system perspective. In some periods RES production can only cover one eight of the electricity demand, and in others RES production is twice the electricity demand.

- Also, two very different periods should be distinguished and analysed: *worst periods (*where RES production is minimum and peak demand is maximum*)* and *peak-demand periods (*where peak demand is maximum*)*. Traditional system adequacy analyses investigate RES production in peak-demand hours; however, results from this analysis indicate that *worst periods* are the ones that pose a challenge to the system, rather than *peak-demand periods*. An analysis on *worst periods* is needed in order to study how the whole system can meet security of supply with minimum amounts of RES.

- Examine RES production throughout different time spans taking into account intra-daily and daily average changes in consumption. This is especially important as the pattern of the electricity demand will change in the future, and therefore peak-demand hours will be shifted to hours in the day where demand is low and RES production is high, or viceversa.

- In addition, the time span analysis looking into different intra-day scales (i.e. 1-hour, 3-hour, 6-hour, 12-hour, etc) shows what the challenges with RES production in the different time spans analysed are. These conclusions, which go well beyond the purpose of this study, are of great benefit to the current discussion on the storage capacity and flexibility that is needed in the Danish system.

- Evaluate RES production from an integrated energy system approach, with flexible electricity demand, and not only based on classical and inflexible electricity consumption. As decisions in 20 and 30 years time are happening now, it is important that this decision's processes take into account changes in demand patterns, as well as changes on how the electricity and the other energy sectors (transport, heat and industry) will interact. This is addressed in this study by implementing an electricity-only system (which is based on classical and inflexible electricity demand) and an integrated energy system (where the electricity, heat, transport and industrial sector interact, and electricity demand is flexible). Major fifferences of using one and the other have been shown.

- In today's Danish electricity market there is no capacity market for RES. After the research carried out in this project, the question on whether a positive capacity credit can be related to a capacity payment arises. Can a capacity credit above zero be related to any money scheme for the RES of focus? This would indeed allow companies and individuals who invest in RES to have an energy payment and a capacity payment. If the Danish goal is to be a fossil free nation in 2050, it might not be too early to discuss such a tariff system. The discussion could also address whether capacity payments should be part of long-term system planning or of system operation.

VI.III Recommendations for Further Work

The following studies and pieces of work can complement, continue and expand the numerous findings of this project.

- Project results are dependent on the distribution data selected. Different distribution data might lead to different results, although the sensitivity analyses that have been carried out throughout the project indicate minor differences in results if other data are used (a note on the sensitivity analyses of wave and solar PV data can be found in “”). For future analysis it is suggested to run EnergyPLAN model and the capacity credit model with distribution data from other years in order to take into account yearly variability of RES.

- With regards to the previous remark, it is also suggested to improve the distribution data for wave power by adding a third wave point. The current wave data file is based on wave measurements at two nearshore locations of the Danish Northe Sea, Horns Rev 3 and Hanstholm. If wave data from an offshore location like Ekofisk is available, also for year 2013, the distribution file for wave production will be more representative of the contribution that wave power can provide to the Danish system, as geographical dispersion and a further offshore location would be taken into account in the distribution file.

- Run an alternative integrated energy system's modelling tool that considers international interconnections, and compare these results with the ones presented in this report.

- Create ENS Wind 2035 scenario and compare the results with those presented here for CEESA2030-modified Scenario.

- Carry out an economic analysis: investigate the same scenarios as investigated in this report and draw conclusions from a solely-economic point of view.
  - Optimise future Danish scenarios with high penetration of RES, in terms of minimum LCOE and minimum system expenditures (in terms of CAPEX).
  - Electricity and gas export and import prices in the calculations could be included.
  - Evaluate integration costs of RES.

- Investigate deeper into existing and planned reserve capacity.

- Investigate day-ahead and intra-day power forecasting of variable RES and how that affect system operation.

- For the selected critical hours in a year, cross-check RES production with conventional production. If there is lack of data on the operation of conventional power plants, it can be assumed that power plants have some failures and require maintenance as modelled with Monte-Carlo simulations (in order to simulate random, unscheduled events).

- Review the concept of capacity payment and study in which timescale it comes into play, i.e. is it part of long-term system planning or of system operation. Can a capacity payment be linked to the capacity credit parameter? Examine which technologies have it and under which requirements in today's electricity system and the projections for future electricity/energy systems.

- In the calculations of the capacity credit of RES, results shown for every time span (i.e. 1-hour, 3-hour, 6-hour, etc…) do not necessarily need to be consecutive; this is, from the same day or hour. The selected time span represents the consecutive hour/hours in a year where the case of study occurs. As future work it is suggested to study the capacity credit of RES in consecutive time spans of 1-hour, 3-hour, 6-hour, etc. It seems very interesting to compare the two set of results obtained.

- Investigate the marginal capacity credit of each of the RES of the study (offshore wind, onshore wind, wave and solar PV), i.e. how the capacity credit changes when adding one unit more of the same technology to an existing renewable energy mix.

Chapter VII – Project Dissemination

The project started with a kick-off meeting hosted by Energinet.dk with all project partners as well as three representatives from Energinet.dk (Loui Algren, Nils Ejner Helstrup Jensen and Preben Nyeng).

Since the beginning of the project regular status meetings have been held among project partners according to the project development and project needs. There are minutes of all meetings, which can be presented upon request.

As explained in Chapter III.V the project has put strong efforts in getting realistic power production data from wave and solar PV in Denmark for year 2013. These data have been made publicly available together with explanatory notes about data origin and processing. Due to the uniqueness of the data, it is expected high welcoming of the data by researchers and other interested stakeholders.

The data can be downloaded at the website: http://www.juliafchozas.com/projects/smart-grids-capacity-credit-wave-solar/.

Aalborg's University research portal VBN is also providing a link to the data through the site: http://vbn.aau.dk/en/projects/capacity-credit-of-wave-and-solar-energy(a684b42d-e79a-4e31-b43e-c18c6d51f7e9).html

Also, the EnergyPLAN model of Aalborg University is introducing the wave and solar PV data obtained in this project in its free distributed data files. The files and the model can be downloaded from www.energyplan.eu/

In addition, throughout project's advancement and completion, project objectives and results have been disseminated through the following communication channels. Project results have been discussed in the final Steering Committee meeting before national publication.

Event: Tuesday Lunch Meetings.
Place: Aalborg University, Copenhagen, Denmark.
Date: 12th January 2016.
Participants: The Sustainable Energy Planning Research Group and the Center for Design, Innovation and Sustainable Transition (DIST) of Aalborg University.

Publication channel: Energy Journal of Elsevier.
Submission Date: November 2015 (paper in submission process).
Publication Date: to be confirmed, in 2016.
Publication Title (journal article): "Capacity Credit and Security of Supply: the Case of Renewable Energies in Denmark".

Event: Dissemination event at Dansk Energi.
Place: Dansk Energi, Copenhagen, Denmark.
Date: 25th November 2015.
Participants: Dansk Energi (Jørgen S. Christensen), Wave Star A/S (Per Ebert), Consulting Engineer Julia F. Chozas and Ole Graabæk (independent consultant).

Event: Final Steering Committee meeting.
Place: Aalborg University, Copenhagen, Denmark.

Date: 12th November 2015.
Participants: Energinet.dk, Aalborg University, Wave Star A/S, Consulting Engineer Julia F. Chozas.

Event: 14th Wind Integration Workshop, WIW2015.
Place: Brussels, Belgium.
Date: October 2015.
Title of the paper: "Capacity Credit and System Adequacy: the Case of Wind, Wave and Solar PV in the Danish System".
Session: Modelling of wind turbines and wind power plants for system integration studies including methods of testing and verification of compliance with requirements and technologies to facilitate integration.

- Paper available in "Annex IX. Paper presented and published at the 14th Wind Integration Workshop Proceedings."

Event: SDEWES 2015, 10th Conference on Sustainable Development of Energy, Water and Environment Systems.
Place: Dubrovnik, Croatia.
Date: September 2015.
Title of the presentation and paper: "Capacity Credit and Security of Supply: the Case of Renewable Energies in Denmark".
Session: Smart Energy Europe: Challenges and Opportunities for a fossil and nuclear free European continent.

- Paper available in "Annex X. Paper presented and published at the 10th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES Conference), Dubrovnik".

Event: Project status meeting with Energinet.dk.
Place: Fredericia, Denmark.
Date: September 2015.
Title of the presentation: "Capacity Credit and Security of Supply: the Case of Renewable Energies in Denmark"
Target audience: Aja Brodal and Loui Algren.

Event: Project status meeting with Energinet.dk.
Place: Fredericia, Denmark.
Date: September 2014.
Title of the presentation: "Capacity Credit and Security of Supply: the Case of Renewable Energies in Denmark".
Target audience: Loui Algren, Anders Pallesen Jensen and Preben Nyeng.

Event: 7th INORE Symposium. Organized by the International Network of Offshore Renewable Energies.
Place: Santander, Spain.
Date: May 2014.
Title of the presentation: "Towards the Development of Smart Energy Systems: wave energy, solar photovoltaic and offshore wind energy systems".
Target audience: International researchers (mostly at PhD level) on marine energies, including wave and offshore wind.

Besides the set of specific dissemination campaigns described above, project results have been disseminated in the form of a final report and papers to the following national and international stakeholders:

- Department of System Planning at Energinet.dk
- The Danish Partnership of Wave Energy (through Jens Peter Kofoed and Wavestar)
- The Danish Partnership of Solar (through Søren Kjar Bakhoj)
- Dansk Energi (through Jørgen S. Christensen)
- DONG Energy (through Anders Sørrig Mouritzen)
- The Wave Energy Research Group of Aalborg University (through Jens Peter Kofoed)
- The Sustainable Energy Planning Research Group of Aalborg University (through Brian Vad Mathiesen)
- Århus University (through Gorm Andresen)
- The Joint Research Centre of the European Commission (through Davide Magagna)
- The Center for Design, Innovation and Sustainable Transition (DIST) of Aalborg University (through Peter Karnøe, Jens Stissing Jensen and John Holten-Andersen)

Chapter VIII – References

Andresen G. "Solar energy can be an important part of Denmark's green transition (Solenergi kan blive en vigtig brik i Danmarks grønne omstilling)". Mandag Morgen, September 17th, 2012. [Available online] www.mm.dk/solenergi-kan-bliv, 2012.

AnemosPlus. [Available online]: www.anemos-plus.eu

Babarit A., Ben Ahmed H., Clément A. and Debusschere V. "Simulation of electricity supply of an Atlantic island by offshore wind turbines and wave energy converters associated with a medium scale local energy storage". Renewable Energy, Vol. 31, pp. 153-169, 2006.

Cradden L., Mouslim H., Duperray O. and Ingram D. (2011). "Joint Exploitation of Wave and Offshore Wind Power", in Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC). Southampton.

Danfoss CLX database, [Available online]: www.clxportal.danfoss.com/da_DK/PlantList. Danfoss inverters.

DMI, www.dmi.dk, accessed in August 2015. The Danish Meteorological Institute (DMI).

DMI, "Vejret i Danmark året 2013". The Danish Meteorological Institute (DMI). [Available online]: www.dmi.dk/vejr/arkiver/maanedsaesonaar/vejret-i-danmark-aaret-2013/

DMI, "Vejret i Danmark året 2014". The Danish Meteorological Institute (DMI). [Available online]: www.dmi.dk/vejr/arkiver/maanedsaesonaar/201402/vejret-i-danmark-aaret-2014

ECI. "Variability of UK Marine Resources". Environmental Change Institute (ECI), University of Oxford and The Carbon Trust, 2005.

ECI. "Diversified renewable energy sources". Environmental Change Institute (ECI) and The Carbon Trust, 2006.

Energinet.dk. "Energi 2050 – Vindsporet". Energinet.dk, Dok.6357/11, Sag 10/3378, 2011.

Energinet.dk, "Systemplan 2013". Energinet.dk, 2013. [Available online]: www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Om%20os/Systemplan_2013.pdf

Energinet.dk, meeting at Energinet.dk with A. Pallesen Jensen (8/9/2914), 2014.

Energinet.dk. "Energinet.dk's analyseforudsætninger 2014-2035". Energinet.dk, 2015.

Energinet.dk, [Available online]: www.energinet.dk, 2015.

Energistyrelsen. "Technology Data for Energy Plants. Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion". Energistyrelsen (Danish Energy Authority). May 2012 (certain updates made October 2013, January 2014 and March 2015), 2012.

Energistyrelsen. “Energiscenarier frem mod 2020, 2035 og 2050 (Energy Scenarios for 2020, 2035 and 2050)”. Energistyrelsen (Danish Energy Authority), 2014. [Available online]: http://www.ens.dk/sites/ens.dk/files/dokumenter/publikationer/downloads/energiscenarier_-_analyse_2014_web.pdf

EnergyPLAN. “EnergyPLAN: Advanced Energy System Analysis Computer Model”. Aalborg University. [Available online]: www.energyplan.eu, 2015.

ENTSO-E, “Definitions and Acronyms”, 2014. [Available online]: https://emr.entsoe.eu/glossary/bin/view/GlossaryCode/GlossaryIndex

ENTSO-E, “Scenario Outlook and System Adequacy Forecast 2011-2025”. European Network of Transmission System Operators for Electricity (ENTSO-E), 2010.

ENTSO-E, “Scenario Outlook and Adequacy Forecast 2013-2030”. European Network of Transmission System Operators for Electricity (ENTSO-E), 2013.

EWEA. “Wind Energy The Facts”. European Wind Energy Association (EWEA), 2009.

Fernández-Chozas, J. “Technical and Non-technical Issues Towards the Commercialisation of Wave Energy Converters”. PhD Thesis (DCE Thesis no. 44), Aalborg University, 2013.

Fernández Chozas, J., Sørensen, H.C. and Kofoed, J.P. “Final project report: Analysis of Power Output Predictability of Wave and Wind”. Energinet.dk, PSO project 10791, 2013.

Fusco, F, Nolan, G and Ringwood, JV. “Variability reduction through optimal combination of wind/wave resources - An Irish case study”. Energy 35, 2010, pp. 314-325.

Giebel, G. “Wind power has a capacity credit – A catalogue of 50+ supporting studies”. Wind Eng E Journal, 2005.

Gross, R; Heptonstall, P; Leach, M; Anderson, D; Green, T and Skea, J. “Renewables and the grid: understanding intermittency”. Energy 160, Proceedings of the Institution of Civil Engineers, 2007, pp. 31-41.

Heide D., von Bremen L., Greiner M., Hoffmann C., Speckmann M., and Bofinger S., “Seasonal optimal mix of wind and solar power in a future, highly renewable Europe”. Renewable Energy 35. pp. 2483-2489, 2010.

Holttinen H. (2005). “Optimal electricity market for wind power”. Energy Policy.

Hvelplund F. “Bedre samfundsøkonomi, gennem integration af vindel og varmemarkedet og fastholdelse af decentral kraftvarmekapacitet”. Institut for Planlægning, Aalborg Universitet, 2014.

IEA, “Harnessing Variable Renewables - A Guide to the Balancing Challenge”. International Energy Agency (IEA), 2011.

Kofoed J.P. “Ressourceopgørelse for bølgekraft i Danmark”. Report No.59 for the Clima Commission, 2009.

Kramer, M.M., Vidal, E., Marquis, L. and Frigaard, P. “Status and perspectives for the Wavestar demonstrator at Hanstholm”, in Proceedings of the 10th European Wave and Tidal Energy Conference (EWTEC´13), Aalborg, 2013.

Kramer M., Marquis L., and Frigaard P. “Performance Evaluation of the Wavestar Prototype”, in Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC). Southampton, 2011.

Lorenz, E.; Kühnert, J.; Wolff, B.; Hammer, A.; Kramer, O.; Heinemann, D., “Power predictions on different spatial and temporal scales integrating PV measurements, satellite data and numerical weather predictions” in EU PVSEC 2014 Conference, Amsterdam, 2014.

Lund, H. “Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply”. Renewable Energy 31, 2006, pp. 503-515.

Lund, H, Hvelplund, F, Mathiesen, BV, Østergaard, PA, Christensen, P., Connolly, D., et.al. “Coherent Energy and Environmental System Analysis”. Aalborg University, Department of Development and Planning, Technology, Environment and Society, 2011.

Lund H. “International Conference on Smart Energy Systems and 4th Generation District Heating”. Aalborg University, 2015.

Lund, H., Andersen, A. N., Østergaard, P. A., Mathiesen, B. V., and Connolly, D. “From electricity smart grids to smart energy systems: A market operation based approach and understanding”. Energy, 42(1), 96-102, 2012.

Martí I., G. Kariniotakis, P. Pinson, I. Sanchez, T. S. Nielsen, H. Madsen, G. Giebel, J. Usaola,A.M., Palomares, R. Brownsword, J. Tambke, U. Focken, M. Lange, G. Sideratos, G. Descombes. “Evaluation of Advanced Wind Power Forecasting Models – Results of the Anemos Project” in Proceedings of the European Wind Energy Conference and Exhibition, Athens, 2006.

Mathiesen, B. V. and Lund, H. “Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources”. IET Renewable Power Generation, 3(2), 190-204, 2009.

Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P. A., Möller, B, et al. “Smart Energy Systems for coherent 100% renewable energy and transport solutions”. Applied Energy, 145, 139–154, 2015.

Mathiesen, B. V., Lund, H. and Karlsson, K. “100% Renewable energy systems, climate mitigation and economic growth”. Applied Energy, 88(2), 488-501. 10.1016/j.apenergy.2010.03.001, 2011.

Milborrow D. “Memorandum by David Milborrow”. Report, 2003.

Nielsen, K; Krogh, J; Helstrup Jensen, N.E.; Kofoed, J.P.; Friis-Madsen, E; Vang Mikkelsen, B; Jensen, A. “Bølgekraftteknologi: Strategi for forskning, udvikling og demonstration 2012”. Partnership of Wave Energy, Aalborg University, DCE Technical Report 146, 2012.

Nielsen P. “Danish Wind Index”. EMD, [Available online]: http://www.vindstat.dk/, 2015.

Nord Pool Spot, [Available online]: www.nordpoolspot.dk, 2015.

Nord Pool Spot, “The Nordic electricity Exchange and the Nordic Model for a Liberalised Electricity Market”. Nord Pool Spot, 2009.

NREL, “Using wind and solar to reliably meet electricity demand”. National Renewable Energy Laboratory (NREL), NREL/FS-6A20-63038, 2015.

OECD/IEAa. “World Energy Outlook”. Organisation for Economic Co-operation and Development /International Energy Agency (OECD/IEA), 2011.

OECD/IEAb. “World Energy Model - Modelling the capacity credit of renewable energy sources”. Organisation for Economic Co-operation and Development /International Energy Agency (OECD/IEA), 2011.

Pecher A., Kofoed J.P. and Larsen T. “Design Specifications for the Hanstholm WEPTOS Wave energy Converter”, Energies 2012, 5, 1001-1017; doi:10.3390/en5041001, 2012.

Pecher A., Kofoed J.P. and Larsen T. “The extensive R&D behind the Weptos WEC”. RENEW Conference, Lisbon, 2014.

Ramboll. “Kortlægning af Bølgeenergiforhold i den Danske del af Nordsøen”. Ramboll, Danish Hydraulic Institute, Danish Metereological Institute, 1999.

Ridjan I. “Integrated Electrofuels and Renewable Energy Systems”. PhD Thesis defended in public at Aalborg University on 28th August 2015, 2015.

Safewind, [Available online]: www.safewind.eu

Smart Energy Systems, [Available online]: www.SmartEnergySystems.eu

Soerensen H.C., Nielsen K., Steenstrup P., Friis-Madsen E. and Wigant L. “Bølgekraftanlæg ved Horns Rev – Screening (Wave energy deployment at Horns Rev Wind Farm)”. 2004 PSO project 5705. 2005.

Soerensen H.C and Friis-Madsen E. “Wave Dragon from Demonstration to Market” in Proceedings of the 3rd International Conference on Ocean Energy, Bilbao, 2010.

Stoutenburg E., Jenkins N. and Jacobson M. “Power Output Variability of Co-located offshore wind turbines and wave energy converters in California”. Renewable Energy, 2010.

Tedd , J.; Kofoed , J.P.; Knapp, W.; Friis-Madsen, E.; Sørensen, H.C., “Wave Dragon, prototype wave power production”. World Renewable Energy Congress, Florence, 2006.

UKERC, “The Costs and Impacts of Intermittency”. UK Energy Research Centre (UKERC), 2006.

Annex I. Glossary of Electricity Systems

This glossary is a compendium of different sources: Gross et al. (2007), Nord Pool Spot (2009), Nord Pool Spot (Nor1) and ENTSO-E (2014). Some of the text has been copied from these references. Further information on electricity terms can be found in (ENTSO-E, 2014).

Adequacy Level: Remaining Capacity minus Adequacy Reference Margin (ENTSO-E, 2014)

Adequacy Reference Margin (ARM) is the margin between generation capacity and expected peak load. This parameter is directly related to system reliability. It is that part of the Net Generation Capacity that should be kept available at all times to insure the security of supply for the whole period of which each reference point is representative. ARM is calculated in order to cover the increase of load from the reference time point to the peak load and demand variations or longer-term generation outages not covered by **operational reserves**. ARM accounts for unexpected events affecting load and generation.

- ARM in an individual country is equal to spare capacity plus the related MaPL.
- ARM in a set of countries (regional blocks or the whole ENTSO-E) is estimated as the sum of all individual MaPL values + spare capacity for a set of countries.

Ancillary services: (*ancillary: auxiliary, secundario*)
(Lund, 2006) says: the following restrictions in ancillary services in order to achieve grid stability apply:

- At least 30% of the power (at any hour) must come from power production units capable of supplying ancillary services.
- At least 350 MW running capacity in big power stations must be available at any moment.
- Distributed generation from CHP and RES are not capable of supplying ancillary services.

Balancing mechanism: Set of arrangements in place after *gate closure* in which the TSO can take bids and offers to balance the system. The prices of bids and offers are determined by market participants and, once accepted, are firm contracts, paid at the bid price. These bilateral contracts are between market participants and the TSO.

Balancing services: Services purchased from balancing service providers by the TSO; includes balancing mechanism bids and offers, other energy trades, *response services*, *reserve services* and other system services.

Balancing energy: electricity that the retailer trades with the *TSO* to balance between the retailer's total trading and the retailer's customers' consumption. Also the electricity a producer settles with the TSO if he fails to produce according to his plan. Balancing energy is related to *reserve services*. In some countries peak load reserves can be bid as balance regulation but the bids will be first offered to the day-ahead spot market.

Bidding area: due to grid bottlenecks, one power exchange system might be divided in various bidding areas.

*Capacity credit***:** measure of the amount of load that can be served on an electricity system by intermittent plant with no increase in the loss-of-load probability (LOLP); often expressed in terms of conventional thermal capacity that an intermittent generator can replace without compromising system reliability. A value of 100% denotes one-for-one substitution with no loss of system reliability and 0% indicates that the intermittent source can displace no conventional capacity.

Capacity factor: energy produced by a generator as a percentage of that which would be achieved if the generator were to operate at maximum output 100% of the time. Capacity factor is sometimes combined with a related term, *load factor*, this differing from the former in that it is a measure of actual utilisation (h/y) rather than maximum output (%).

Dispatchable capacity: capacity that can be turn on and off when needed.

Dispatchable units: units which output can be controlled by the operator of the unit or by the TSO, i.e. units that allow total control of the power output. It has usually been used to describe conventional power generation, biomass and hydropower. For example, wind is regarded as non-dispatchable renewable capacity; although modern wind turbines are controllable (to a degree) they are generally not considered dispatchable.

Dispatchable technologies: technologies that can be called upon to operate at any given time (allowing for downtime for maintenance, which in older plants can be considerable). As a result, system managers can rely on their output and manage them in a conventional manner (IEA, 2011).

Electricity markets: a market composed by commercial and non-commercial players. The commercial players trade with electricity and are not responsible for the security of supply; they only deliver the prices – they only deliver financial services. The non-commercial players are those responsible of security of supply, i.e. the TSOs.

- *Financial or bilateral electricity market*: financial domain of electricity markets, which appeared when electricity markets were liberalised. It is run by financial or commercial players. Trading takes place bilaterally (over the counter) outside the power exchange, and prices and amounts are not made public. In the financial market, the parties of a financial contract do not trade energy (not kWh), only money; the financial market is used for price hedging and risk management. It is the market for long-term contracts, i.e. future and forward contracts. It is also used to trade electricity among players in different bidding areas.

- *Day-ahead market (spot market)*: a physical market in which prices and amounts are based on supply and demand. The spot market is a day-ahead market that trades with deliveries from midnight to 36 hours ahead.
    - *Elspot:* Nord Pool Spot's day-ahead double auction market, where electrical energy is traded. It represents a double auction as both the buyers and the sellers submit their bids. Those who want to buy electricity from Elspot must send their purchase bids at the latest at noon the day before the energy is delivered to the grid. Correspondingly, those who want to sell energy must send their sale offers at the latest at noon the day before the energy is delivered to the grid. Each order specifies the volume (MWh/h) and the specific price levels (EUR/MWh) for each individual hour in the following day.

      Elspot calculates the day-ahead prices i.e. an hourly price which balances the bids and offers from producers and consumers, and reports participants how much they have bought or sold for each hour of the following day. Hence, Nord Pool Spot publishes a spot price for each hour of the coming day. The Elspot price represents both:

      i) the cost of producing one kWh of power from the most expensive source needed to be employed in order to balance the system (either from a domestic installation or from external imports), and

      ii) the price that the consumer group is willing to pay for the final kWh required to satisfy demand.

    This type of price formation is called *Marginal Price Setting*. It is characterised by the inelasticity of the market to store electricity.

- *Intra-day market*: markets in between the day-ahead market and the regulating power market. It is used to adjust and to minimize the deviations from production and consumption determined in the day-ahead market. Normally, only those participating in the corresponding day-ahead market are allowed to participate in it.
    - BETTA: intra-day UK market.
    - Elbas: intra-day Nord Pool market.
    - In Spain there are 6 intra-day markets.
    - In France there are 24 intra-day markets.

- *Balancing market:* its main function is to provide power regulation to counteract imbalances related to day-ahead planned operation. In the balance market there are two types of participants: active participants (mainly producers but also consumers who can regulate their generation or consumption on request from the TSO – bidding regulation) and passive participants (all companies connected to the central grid). The market closes one hour before the hour of operation.

- *Regulating power market:* a real-time market covering operation within the hour. The main function is to provide power regulation to keep the frequency of the system at 50 Hz.
    - Regulating bids have to be activated to the stated amount within 15 minutes.

Electricity prices: the price of electricity to households and day-ahead electricity prices are different. In Spain, for example, households pay about 150 EUR/MWh, whereas day-ahead electricity price is about 50 EUR/MWh. There are following reasons: the change in voltage level, transport and distribution costs, substations costs, reactive power consumption costs, etc. As a rule, the highest voltage level, the cheapest electricity price.

Energy amortization time or energy payback period: period needed by the power station to generate the energy consumed for all stages of its lifetime from 'craddle' (material extraction for construction) to 'grave' (demolition and disposal). It should be noted that only the energy consumed during plant construction might be considered by some sources.

Energy Yield Factor (of a plant) is the ratio of net energy production during plant life and the cumulative energy used for construction, operation and operating supply items. In simplified terms: it is a factor that indicates how many times energy generated during plant operation covers the energy used for constructing the plant. It should be noted that depending on the source, energy for maintenance works, fuel consumption or energy required for operating the plant, demolition or disposal of the plant, might not be taken into account.

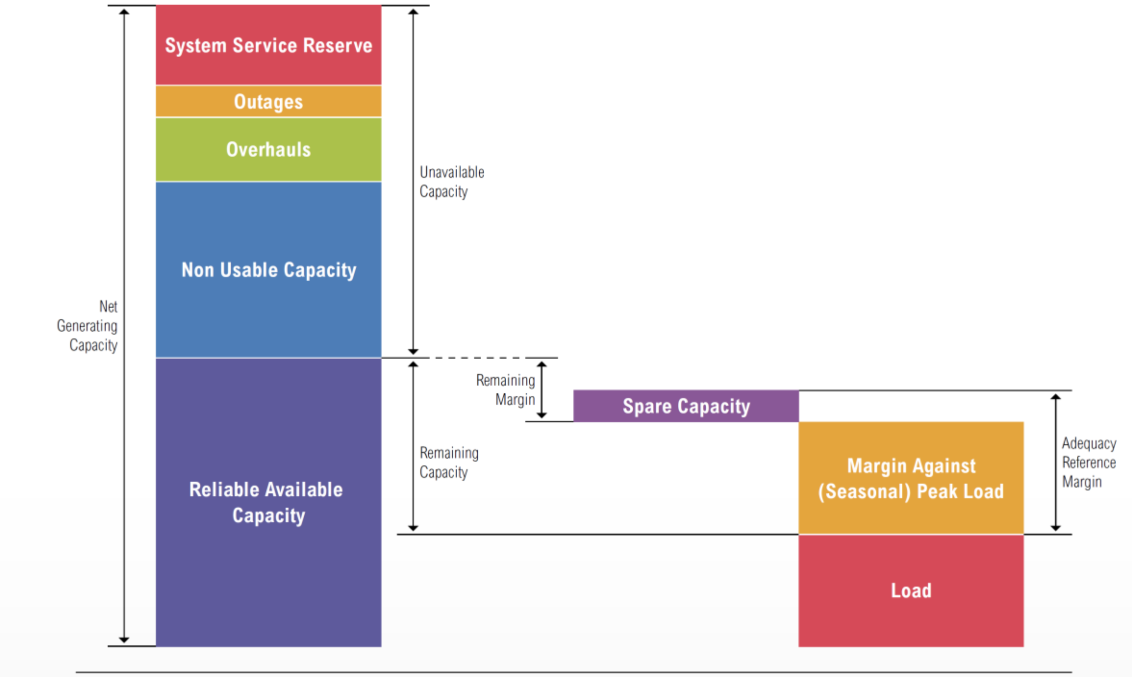
Firm capacity: essentially power supply that can be more or less guaranteed (IEA, 2011).

*Gate closure***:** point in time at which the energy volumes in bilateral contracts between electricity market participants must be notified to the central settlement system. Between gate closure and real time, the TSO is the sole counterparty for contracts to balance demand and supply. There are different gate closures for each market, i.e.:

- Gate closure of Day-ahead markets is usually at noon, i.e. Elspot market in the Nordic region closes at noon.
- Gate closure of intra-day markets, i.e. BETTA in UK or Elbas in the Nordic region, is one hour before the *hour of operation*.

Generation Adequacy of a power system is an assessment of the ability of the generation on the power system to match the consumption on the same power system (ENTSO-E, 2010).

- The concept of Generation Adequacy Analysis is illustrated below:



Grid codes: *a suite of rules set by the system operator (IEA, 2011).*

Hour of operation: hour during which the energy is delivered and consumed.

Loss-of-Load Probability and Loss-of-Load Events: *as the reserve generation margin increases in a given system, the LOLP of the system decreases. Average values for California (ECCO & ERCOT studies) are between 0.001% and 0.018%.*

LOLEV, which is a probability-based average, is calculated as follows,

$$LOLEV = \sum_{i=1}^{15} Probability_i \times LOLEV_i$$

The summation of the product of each load scenario probability and LOLEV for the scenario gives the study-wide LOLEV. In the above formula, i varies from 1 to 15 reflecting the fifteen annual load scenarios.

The reserve margin is calculated by,

$$Reserve\ Margin = \frac{Resources\text{-}\ Median\ Scenario\ Peak\ Load}{Median\ Scenario\ Peak\ Load}$$

where,

$$Resources = (NonWind\_Capacity + ELCC_{Coast} \times WindCapacity_{Coast} + ELCC_{West} \times WindCapacity_{West})$$

Variations in reserve margin are obtained by adjusting the non-wind generation capacity, as previously discussed in the *ERCOT LOLP study Assumptions and Methodology* document. The following reliability indices were estimated for various reserve margin levels.

- The annual Loss of Load Events (LOLEV).
- The annual Loss of Load Hours (LOLH).
- The annual Expected Unserved Energy (EUE).

(http://www.ercot.com/content/gridinfo/resource/2014/reservemargin/ERCOT_Loss_of_Load_Study_2013PartII.pdf)

Margin against Peak Load (MaPL) is the difference between load at the reference point and the peak load over the period for which the reference point is representative (ENTSO-E, 2010). In SO & AF it is actually Margin against Seasonal Peak Load for each reference point. That means:

- One summer value, defined as the difference between the load at the summer reference point and the forecast summer peak load (peak load of quarters 2 and 3 of the reported year) and,
- One winter value, defined as the difference between load at the winter reference point and the forecast winter peak load (peak load of quarters 1 and 4 of the reported year).

Marginal cost: operational cost to produce one more *kWh* of electricity. In electricity markets the competition of a plant depends on the marginal cost.

- *High marginal cost units or Marginal costs units* are the units that enter the bids on peak demands. They are used for peak load generation and flexible generation. They are named as high marginal costs because they normally have high operational costs. It usually corresponds to coal, gas and CCGTs (combined cycle gas turbines) power plants.
- Gas-fired generation has predominantly been the marginal plant type on the Great Britain system, and there has correspondingly been a correlation between the cost of gas-fired generation (including carbon) and Great Britain power price.
- Flexible plants to operate: expensive: coal and natural gas.
- Inflexible plants to operate: cheap: nuclear.

Market price: day-ahead exchange price for a settled hour. For instance, Elspot day-ahead price is the underlying reference for the financial contracts. It is the reference price for futures, forwards and options traded in the financial market.

Market splitting and market coupling: related to the allocation of available cross-border capacities to deal with day-ahead congestion management. This can be done through explicit or implicit capacity auctions. Implicit capacity auctions ensure that the electricity flows from the surplus area (low price areas) toward the deficit areas (high price areas), thus also leading to price convergence.

- *Market splitting*: happens when the limited transmission capacity leads to a split between two market areas. Hence, there are different prices in different bidding areas. Market splitting involves only one electricity exchange, i.e. domestic bottlenecks in Norway or inter-state links of countries.
- *Market coupling:* is the used of implicit auctioning between two or more power exchanges, i.e. coupling of the Nordic and the German day-ahead markets.

Net Generating Capacity (NGC): The NGC of a power station is the maximum electrical net active power it can produce continuously throughout a long period of operation in normal conditions. The NGC of a country is the sum of the individual NGC of all power stations connected to either the transmission grid or to the distribution grid (ENTSO-E, 2010).

Nordel: body for co-operation between the *TSOs* in Denmark, Finland, Iceland, Norway and Sweden towards a Nordic electricity market. It was also a forum for contacts between the TSOs and representatives of the market participants in the same countries. On July 2009, all operational tasks from Nordel were transferred to the *European Network of Transmission System Operators for Electricity* (*ENTSO-E*).

Nord Pool Spot: Nordic electricity market that offers both the day-ahead and the intra-day electricity markets to its participants. It covers Norway, Sweden, Finland and Denmark. In 2010 it had a turnover of 307 TWh, representing 18 billion EUR and 74% of the total electricity consumption in the Nordic countries (i.e. the rest, 26%, were electricity imports, bilateral contracts, etc).

Operating margin: the difference between available generation and actual demand.

Reference Points: specific dates and times for which power data are collected. These points are characteristic enough of the whole studied period to limit the data to be collected to those at the reference points (ENTSO-E, 2010).

Regulating energy: energy the TSO trades in order to keep the frequency at 50 Hz. It is related to the *response services*.

- *Upward-regulation:* when the consumption exceeds the production, the frequency of the alternating current falls to a value below 50 Hz. To counteract it, it is needed to increase generation in the system. In this case, the TSO must buy electricity from the producers.
- *Downward-regulation:* when the production exceeds the consumption, the frequency of the alternating current rises to a value above 50 Hz. To counteract it, it is needed to decrease generation in the system. In this case, the TSO must sell electricity to the producers, thereby causing producers to reduce their production.

Reliable available capacity, RAC: The RAC on a power system is the difference between the NGC (Net Generation Capacity) and the Unavailable Capacity. The RAC is the part of the NGC that is actually available to cover the load at a reference point (ENTSO-E, 2014).

*Response services***:** services purchased by the TSO in order to ensure there is sufficient capability in the short-term to undertake frequency control. It may be utilised <u>in seconds</u> through <u>automatic controls</u> on generators or loads. Steam generators may be held below maximum output to facilitate this.

- There are primary, automatic and manual reserves

Reserve services: services purchased by the TSO in order to ensure there is sufficient capability in the short-term to undertake system balancing actions. It is a capability to change output to meet TSO requests <u>within a few minutes</u>. Utilisation of this capability may be subject to payment in the balancing mechanism or through other balancing service agreements. There are various categories of reserve depending on speed of delivery and the nature of its provision. Fast reserve can be provided by demand reduction, pump storage or part-loaded steam plant connected to the system. The term ‘<u>spinning reserve’</u> has in the past been used to describe a generator that is spinning and ready at very short notice to contribute power to the system.

- *Standing reserve* is ready for action within 20 minutes. As well as demand reductions it might consist of fast starting gas turbines or backup diesel generation.
- *Residual reserve* is the capability provided in the balancing mechanism, i.e. reserves that can be dispatched in response to market prices rather than contracted by the TSO.
- *Contingency reserve* is the capacity that should be established in the 24 hour-ahead period by the market. It is not usually purchased by the TSO but is monitored to ensure adequate short-term reserves will be available.
- *→ OJO! There are **Operational reserves** and Other Reserves (NISU) **– related to ARM***

Smart Energy Systems: The Smart Energy Systems approach builds upon a sectorial integration approach. It focuses on the integration and merging of the electricity sector, the heating sector and the transport sector, enabling the use of infrastructures and energy storages across all energy carriers (www.SmartEnergySystems.eu).
Smart Grids: Smart grids refer to the different technologies solely within the electricity sector that contribute to increase the prevalence of renewable energy in the system.

> *As Poul Frederik Bach indicates, "It is easy to decide new green electricity production. It is more difficult to foresee the behavior of the energy system. The practical result could be a gradually phasing out of CHP. 'Smart Grid' is a magic word, which is supposed to solve the problems. The green development is controlled by economic incentives".*

Spare Capacity: that part of the Net Generation Capacity which should be kept available at reference points to ensure the security of supply in most of the situations. Spare Capacity is supposed to cover a 1 % risk of shortfall on a power system, i. e. to guarantee operation in 99 % of situations. Spare Capacity is estimated by the TSOs in each country depending on its system's features, and for a set of countries (regions or whole ENTSO-E) as 5 % of Net Generation Capacity (ENTSO-E, 2010).

System adequacy**:** ability of the electricity system to meet electricity demand at all times (even at peak times) with an acceptably high probability (OECD/IEAa, 2011) *(suficiencia del sistema).* (EWEA, 2009), (ENTSO-E, 2010): System adequacy measures the **ability** of a power system to supply the load in all the steady states it may operate in under standard conditions. This adequacy has different components:

- The ability of the generation assets to cover the peak load, taking into account uncertainties in the generation availability and load level; and
- The ability of the transmission system to perform, considering the flexibility provided by interconnection and import and export flows.

System margin: difference between installed capacity, including imports and exports, and peak demand. Historically, the concept has been referred to as *capacity margin*, *system reserves* and *plant margin*.

System balancing reserves maybe thought of as an operational issue – what is needed to manage the system at each and every hour of the day, throughout the year. By contrast, system margin may be thought of as a planning issue – an overall 'margin of error' that was historically designed into centrally planned electricity networks.

The distinction between the system margin required for longer-term reliability and reserves required for short-term balancing is illuminated by the comparative size of the two quantities. In the UK, balancing reserves are purchased by the TSO and comprise about 4% of peak demand (in 2006). System margin is much larger than dedicated reserve and it is not contracted for: in 2006 the indicative level of adequate system margin was around 20% above current expected peak demand, including exports (Gross, et al., 2007).

The *plant margin* is the total amount of generating plant that an electricity system needs, over and above the maximum demand, to guarantee supplies. With an all-thermal system, that margin is about 15%. The introduction of any intermittent plant onto an electricity network increases the "apparent" plant margin, since the capacity credit of the former is lower than the latter. And this does not affect the ability of all the generating plants to deliver high reliability (Milborrow, 2003).

System operators: bodies responsible for their area to be electrically stable, i.e. frequency to be kept at 50 Hz. They are also responsible for the security of supply in their area. They have to be a non-commercial organization, neutral and independent with regard to market participants. In several countries, the system operators are also responsible for the high-voltage grid, hence the name *Transmission System Operators*.

System Reserve: means Active or Reactive Power reserves to actively manage the network predominantly to respond to Frequency and Voltage fluctuations [ENTSO-E Glossary].

Transmission System Operators (TSOs): bodies responsible for the security of supply in their countries. They also own and operate the high voltage grid. Consequently, the TSOs own, rule and operate the electricity system in their countries. National Grid undertakes this role in Great Britain, Energinet.dk in Denmark, Statnett in Norway, Svenska Kraftnät in Sweden, Fingrid in Finland and Red Eléctrica de España in Spain.

Unavailable Capacity: part of the NGC that is not reliably available to power plant operators owing to the limitations of the output power of power plants. It consists of Non-Usable Capacity (resulting from the variability of the primary sources like wind, hydro or solar sources), Maintenance and Overhauls, Outages and System Services Reserve (ENTSO-E, 2010).

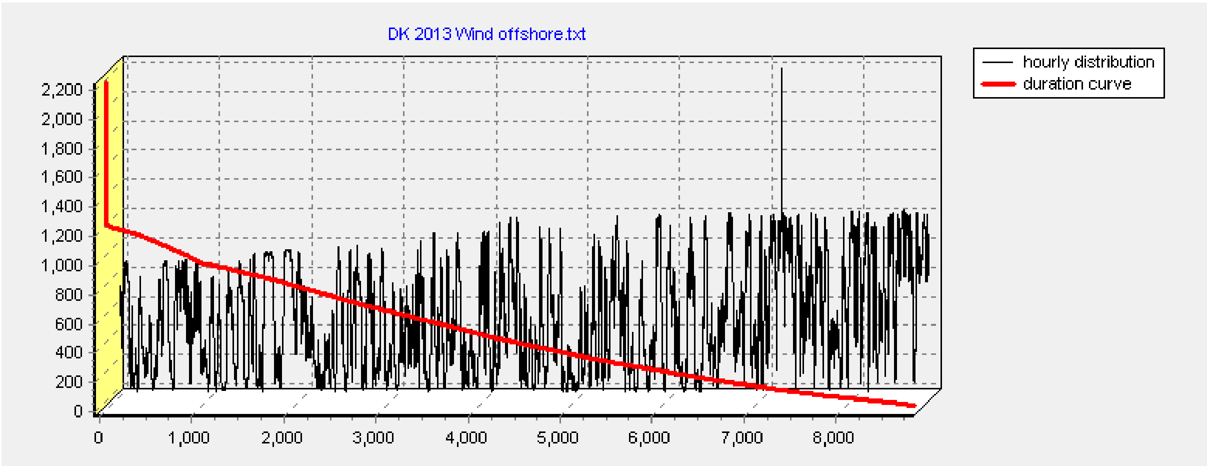
Annex II. Note on 2013 Wind Distribution Data

Date: April, 2015

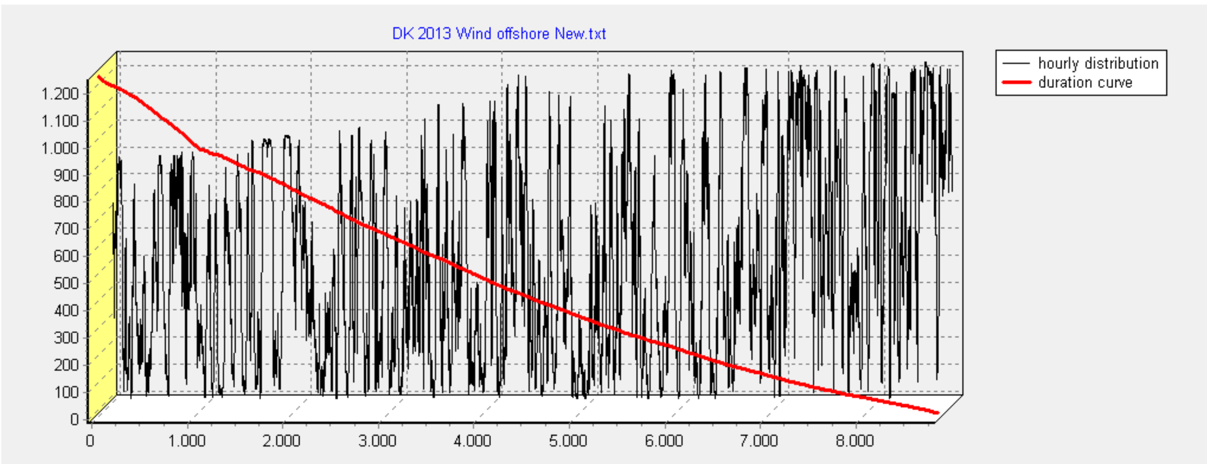
Authors: Julia F. Chozas

'DK 2013 Wind offshore'

Original file:



- **Original file** '*DK 2013 Wind offshore*':
    - Max values are around 1200 (MW)
    - Peak of 2209,2 (MW) on 27.10.2013 at 2:00
- New file '*DK 2013 Wind offshore New*':
    - Hourly value of 27.10.2013 at 2:00 calculated as a linear average of the previous and following hour by interpolation:
        - 27.10.2013 at 1:00 equals: 1094,4
        - 27.10.2013 at 3:00 equals: 1134,7
            - 27.10.2013 at 2:00 --> 1114,6



FILES COMPARISON

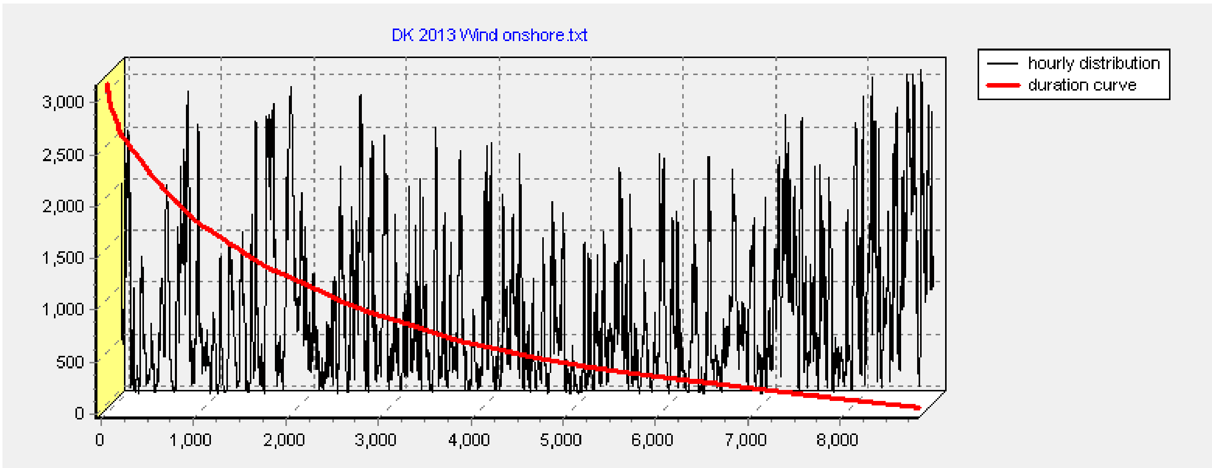
- Scenario: ‘2013 Dk reference’
- Offshore wind: 1271 MW

Comparison of Output results with (old) file: ‘*DK 2013 Wind offshore*’ and with updated file ‘*DK 2013 Wind offshore New*’:

	Offshore Wind Prod. (TWh/y)	Coal (TWh/y)	Oil (TWh/y)	N. Gas (TWh/y)	Biomass (TWh/y)	Renewable (TWh/y)	Total Fuel Consumption (TWh/y)	Excess production CEEP (TWh/y)		Total Costs (MDKK)	Marginal Operation Costs (MDKK)	Total CO2 emission costs (MDKK)
OLD file	4,35	35,58	79,19	37,43	41,03	12,1	205,32	0,08	0	49811	399	4783
NEW file	6,22	33,42	79,73	37,02	40,53	13,97	204,67	0,3	0	49662	372	4702

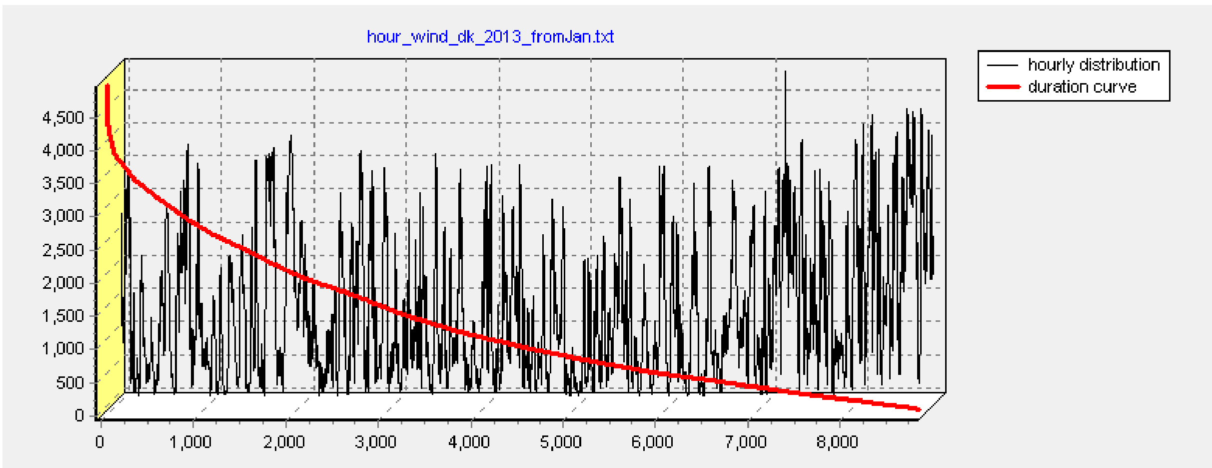
’DK 2013 Wind onshore’

No problems:



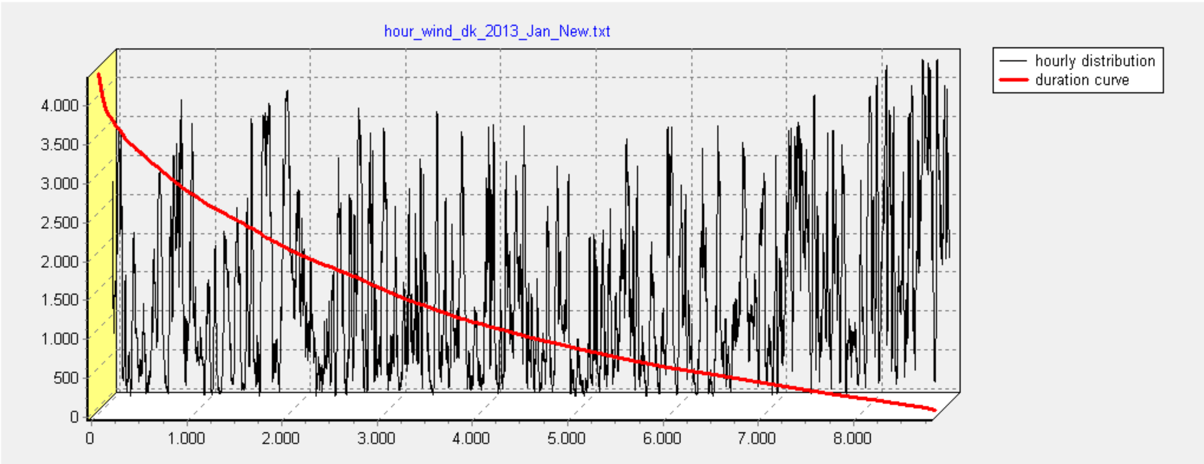
‘hour_wind_dk_2013’ (from Jan)

Original file:



- **Original file** ‘*hour_wind_dk_2013_Jan*’:
    - Maximum values are around 4300 (MW)

    - Peak of 4892,5 (MW) on 27.10.2013 at 2:00
- New file 'hour_wind_dk_2013_Jan_New':
    - Hourly value of 27.10.2013 at 2:00 calculated as a linear average of the previous and following hour by interpolation:
        - 27.10.2013 at 1:00 equals: 2463,5
        - 27.10.2013 at 3:00 equals: 2546,2
            - 27.10.2013 at 2:00 --> 2504,9



Relevant documents:

- *Output prints of EnergyPLAN*
- *Excel file: 'DK 2013 Wind offshore Comparison'*

Annex III. Note on 2013 Solar PV Distribution Data

Date: 27th May, 2015
Authors:
Julia F. Chozas[5] and Søren Bækhøj Kjær[6]

This note describes the process to obtain representative hourly solar power production data for Denmark, to be included as a Distribution File for EnergyPLAN model. Reference year is 2013.

Baseline data

- **Danfoss CLX database**
  - Source: http://clxportal.danfoss.com/da_DK/PlantList (data from Danfoss inverters)
    - http://clxportal.danfoss.com/
    - Data from solar PV plants around the world
    - In DK: 2027 plants
    - Installation date ranges from 2008 to 2015, although generally ranges from 2012 (solar PV boom in Denmark on 2012 to 2013)
    - Size: 1 kW to 2100 kW
    - Resolution: 10 or 15-minute data

Data processing

- Data retrieval:
  - Commissioned to Papendorf Software Engineering GmbH.
  - 2 files:
    - *'Plants': 2027entries* - Post code, name of the house, installed capacity, etc…
    - '*data*': production data for each entry

- Post-data processing:
  - Thorngreen Thomas Kure <Thomas.Thorngreen@danfoss.com>
  - Søren Bækhøj Kjær <sbk@danfoss.com>
  - File: 'CLXData2013&2014.csv'
    - From 01.01.2013 to 31.12.2014
    - Full-load hours (FLH (h))

FLH(h) is defined as <Power production (kWh)/Installed capacity (kW)>

Main comments (from Søren Bækhøj Kjær, 21st May)

The following production units have been deleted / discarded from the original file, in order to get better quality of data:

Systems with data in the CLX portal before the system is commissioned are not included. *Rational: Data from a non-commissioned system might be corrupted.*
Only systems installed in 2012 and 2013 *Rational: Systems before 2012 might have a lower yield than newer systems. Systems after 2013 are not of interest in this project, since it focuses on year 2013.*

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Systems installed later than Sept. 2013 are not included. *Rational: The production from solar PV systems in October-December is low, thus using these systems would not bring much more accuracy to the data.*
Systems below 3.68 kW are not included. *Rational: Single-phase solar PV systems are not included (Limit is 16 A). They might have problems with over-voltages on the electrical grid, reducing their yield.*
Systems installed in 2012 but with less than 1600 full-load hours in the years 2013 and 2014 (sum of Y2013 and Y2014) are not included. *Rational: If the yield is below 800 full-load hours per year, then either the solar PV plant is placed in "non-optimal" conditions or there are other problems with the plant.*
Systems installed in 2013 but with less than 800 full-load hours in the years 2013 and 2014 (sum of Y2013 and Y2014) are not included. *Rational: If the yield is below 800 full-load hours per year, then either the solar PV plant is placed in "non-optimal" conditions or there are other problems with the plant.*
Systems with more than 1200 full-load hours are not included. *Rational: The yield for non-concentrating or fixed direction will not exceed 1200 full-load hours per year, even if the over-sizing ration is 1:1.2 (e.g. 7.2 kWp solar PV modules on a 6.0 kW inverter)*
Systems related to Danfoss tests are not included. *Rational: Danfoss might have altered the data-logger software/settings of the solar PV plants themselves, thus possible corrupting data.*

Total installed solar PV capacity in the CLX database:
- On 01.01.2013: 1.4 MW
- On 31.12.2013: 5,7 MW
- On 31.12.2014: 5.9 MW

with a total number of 522 solar PV plants.

The number of full-load hours of each system has been calculated for every hour.

[Note from Søren, 21st May]: "I have visually examined whether the data is synchronous, and it seems to be the case plus / minus one hour. Likewise, I have removed productions below 10.8 kWh per hour to ensure that data achieves ~4560 hours of production data above 0 kWh/h per year (number of anticipated hours where data should be available in the CLX database)"

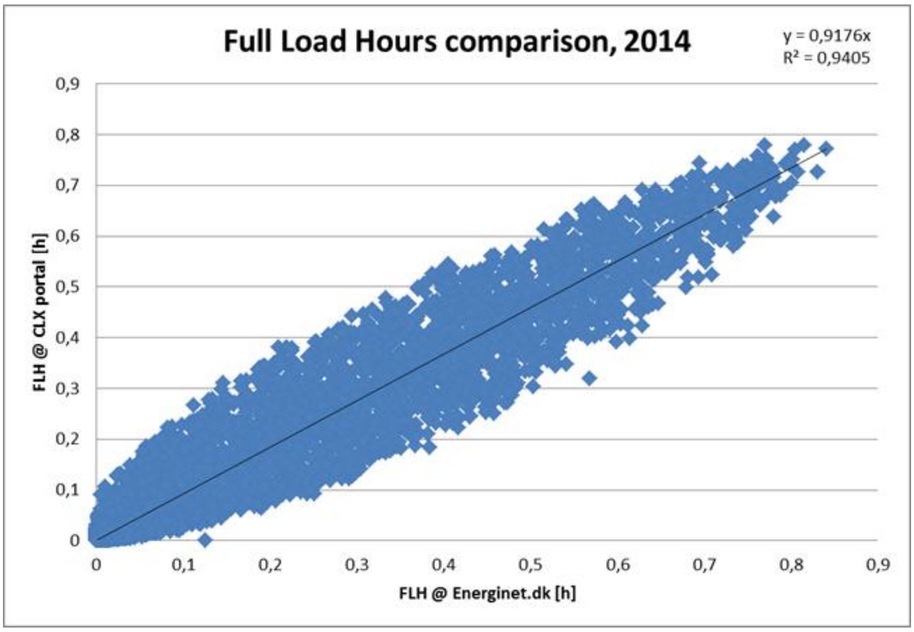
- 365* 12.5 = 4563 hours are the approximate number of hours per year with solar irradiance in Denmark.

The geographical division of units is as follows:

Postal code	*Number of solar PV plants*
0 – 1000	0
1000 – 2000	3
2000 - 3000	48
3000 - 4000	58
4000 - 5000	54
5000 - 6000	83

6000 - 7000	65
7000 - 8000	82
8000 - 9000	88
9000 – 10000	41
Total:	***522***

Correlation-test with Energinet.dk 2014 Data, in order to assure quality of the data received (data should coincide): comparison of full-load hours from PV power production retrieved from Energinet.dk server (corresponding to PV power production of East and West Denmark divided by the average installed capacity in Denmark each month), and CLX/Danfoss retrieved data for year 2014:



According to Energinet.dk data, PV production has 1024 full-load hours; CLX/Danfoss data estimates about 963 full-load hours. Correlation between both datasets is 0.97 (*CORREL* function in EXCELL).

Based on the high correlation of data for year 2014, we can conclude that data for year 2013 is also valid.

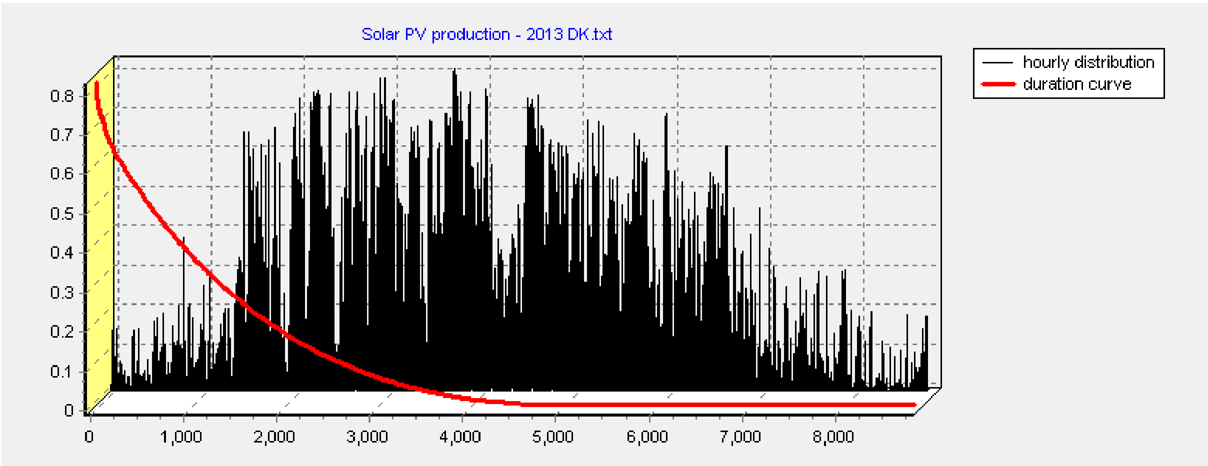
Final Distribution Files

To be included in EnergyPLAN model. EnergyPLAN model takes as input per unit hourly power production. Files are 8784 hours long. Since 2013 has 365 days, the last 24 hours of the year are repeated in order to reach 8784 hours.

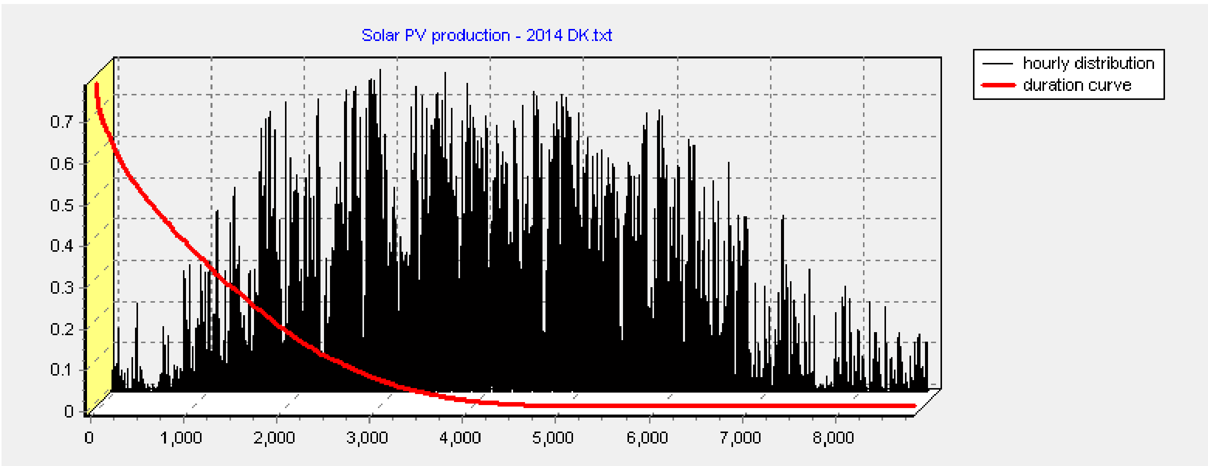
The same is done for year 2014; data comes from the same database, files and procedures mentioned above.

The following distribution files have been created, from the excel file '*CLX data 2013&2014.xlsx*':

- *'Solar PV production - 2013 DK'*
    - Duration curves of the file is represented below:



- *'Solar PV production - 2014 DK'*
  - Duration curves of the file is represented below:



Annex IV. Note on 2013 Wave Distribution Data

Date: April, May, August 2015
Authors: Julia F. Chozas[7], Jens Peter Kofoed[8] and Enrique Vidal Sánchez[9]

This note describes the process to obtain representative hourly wave power production data for Denmark, to be included as a Distribution File for EnergyPLAN model. Reference year is 2013.

Baseline data

- **Horns Rev 3**
  - Source: FTP server Energinet.dk
  - From 2003 to 2013
  - Hourly data
  - *Data indicates the average of the next hour (for one day, data starts in Hour 0 and stops in Hour 23)*
  - Hindcast data developed by COWI
  - Data available for 9 points at Horns Rev3
  - Wave Parameters (among others relevant to wind): H_{m0}, T_{01}, T_{02} and T_p
  - Selection of Point5

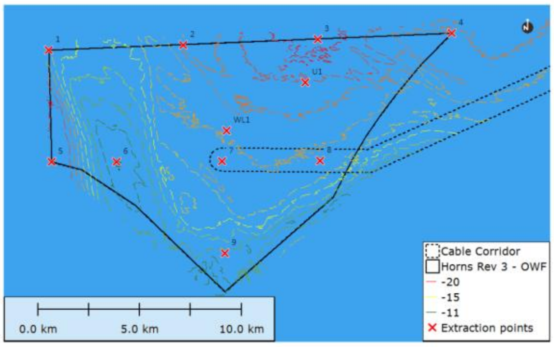


Figure 1.5 Location of data extractions. P1 to P9: Waves conditions from MIKE 21 SW. P7 is the location of the HR3 substation. U1: Wind Conditions (DMI-HIRLAM). WL1: Water levels (DMI-HBM).

Table 1.1 Extraction locations for MIKE21 SW wave model data. Coordinates in UTM32.

MIKE21 WAVE MODEL DATA EXTRACTION POINTS				
Extraction point	Easting (m)	Northing (m)	Seabed level (m LAT)	Seabed level (m DVR90)
P1	408,895	6,177,777	-15.3	-15.8
P2	415,494	6,178,049	-16.8	-17.3
P3	422,091	6,178,332	-20.0	-20.5
P4	428,688	6,178,624	-17.3	-17.8
P5	409,026	6,172,275	-19.3	-19.8
P6	412,231	6,172,283	-10.5	-10.9
P7 (HR3 substation)	417,400	6,172,300	-16.0	-16.5
P8	422,215	6,172,316	-16.3	-16.7
P9	417,549	6,167,771	-12.2	-12.7

- **Hanstholm**
- Source:
  - AAU Civil Eng. Dpt, DanWEC data server – data selected for Year2013
    - Half-hourly timeseries
    - Buoy-measured data
    - *Data indicates the average of the following 30 minutes (for one given day, data starts in Hour 00:00 and ends in Hour 23:30)*
    - Comments on QC of data:
      - Some data missing: 9 days in January, 6 days in Oct, 6 days in Nov, end Dec…
      - (There is a Note on that – attached at the end of this Document)

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[9] Wavestar A/S, www.wavestarenergy.com, evs@wavestarenergy.com

- Kyst.dk - from 2009 to 20.02.2015 – NO data used for this project
    - Web: www.kyst.dk
    - (should be the same as the time-series from AAU)
    - Buoy-measured data
    - Half-hourly timeseries
    - Location and Depth:
        - Ident 1022: 474 700 E 6 332 100 N vanddybden er ca. 17.5m
    - *Data indicates the average of the following 30 minutes (for one given day, data starts in Hour 00:00 and ends in Hour 23:30)*

- From 1979 to 2009: SDWED project – data selected for years 2003-2009
    - Project website: http://www.sdwed.civil.aau.dk/
    - Hourly timeseries
    - Hindcast data
    - Parameters: frequency Domain parameters:

    Starttime,.Hm0,.Te,.T1,.T2,.Tz,.Tp,.Lp,.Pw,.bandwidth,.psd,.timeseries,.normality_x,.normality_y

    - Files available without (version 1) and with (version2) Date and Time
    - *Data indicates the average of the next hour (for one given day, data starts in Hour 0 and ends in Hour 23)*

- **Fjaltring**
    - Source: Kyst.dk (www.kyst.dk)
    - Data from 2009 to 03.04.2015 – data selected for year 2013
    - Buoy-measured data
    - Comments on data & Quality Control (QC):
        - Data available only from Jan2013 to Oct2013
        - other data missing too
        - There is a Note on the QC at the end of this document.
    - Location and Depth:
        - Ident 2031: 441 976 E 6 259 466 N vanddybden er ca. 17.5 m.
    - Available parameters:
        - In first version sent by Kyst: Hm0, Have, Tave
        - In second version sent by Kyst: H_MAX,T_MAX,H_1_10,T_1_10,H_1_3,T_1_3, H_AVG,T_AVG,H_M0,T_M0,T_Z,T_P,DIR,F_P,SPEKDENS_P, SPRED_P,SKEWNES_p,CURTOSIS_p,EPS,PCT_FEJL,PCT_OK, HLF,TEMP,h_mid_shaf,h_max_shaf,T_S1,T_S2,T_C_M, T_AVG_M,T_INT,T_p_m,EPSI2,EPSI4,qp,s2,temp_ref,bat
    - *Data indicates the average of the following 30 minutes (for one given day, data starts in Hour 00:00 and ends in Hour 23:30)*

Missing values

Number of missing data points:

- **Horns Rev 3**
    - Total number of values: 8760
    - Data validity: 100% of the total dataset

- **Hanstholm**
    - Total number of values: 15862
    - Data validity: about 90% of the total dataset
        - *Since the number of missing values does not exceed 85% of the time, the following methodology is considered reasonable.*
- **Fjaltring**
    - Total number of values: 11424
    - Data validity: about 65% of the total dataset
        - *Big number of data points missing.*

Filling-in missing values in the time series

- If gap is of 0.5-hour: the gap is ignored and the previous half-hourly value is assumed
- If gap is 0.5<x=<2.5-hour: make it equal to the average from the two nearest available points – linear interpolation
- If gap is >2.5-hour: calculate an approximate to the missing value from existing data points of other locations, i.e. Horns Rev 3.

Look for the Correlation between datasets A and B, and A and C:

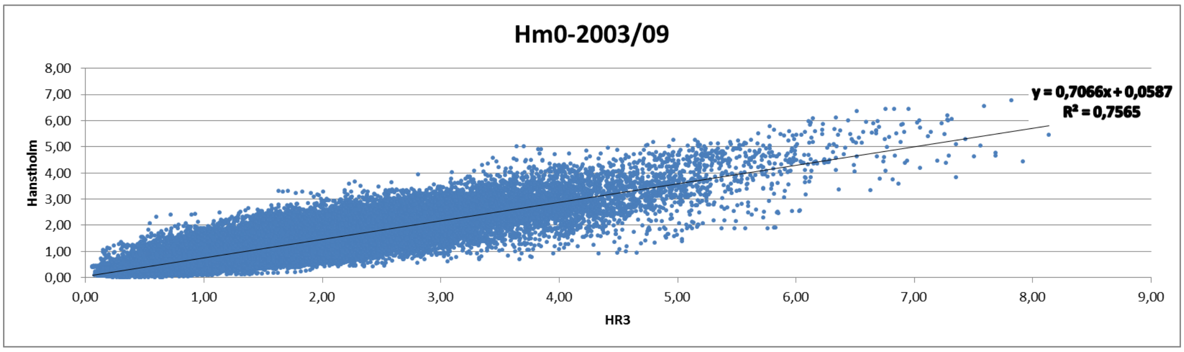
- Dataset A: Horns Rev 3, Pt.5
- Dataset B: Hanstholm SDWED, Pt.5
- Dataset C: Fjaltring

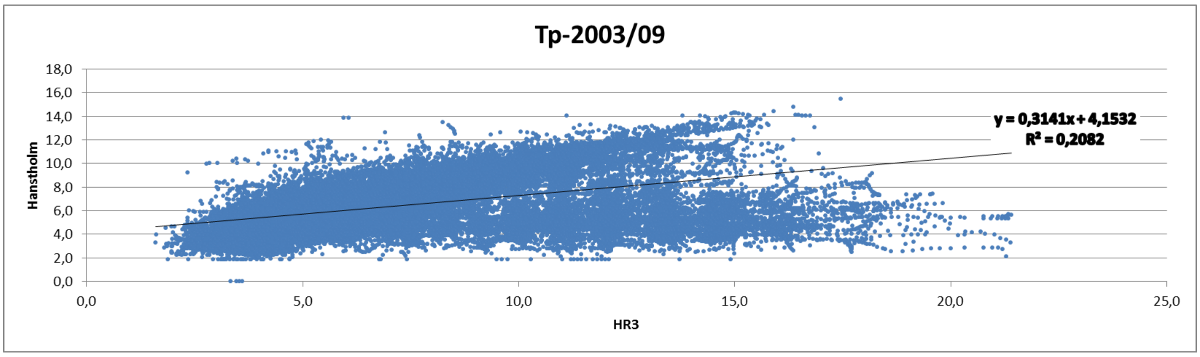
- Correlation (inclination of the line) for the parameters:
    - H_{m0}
    - T_p

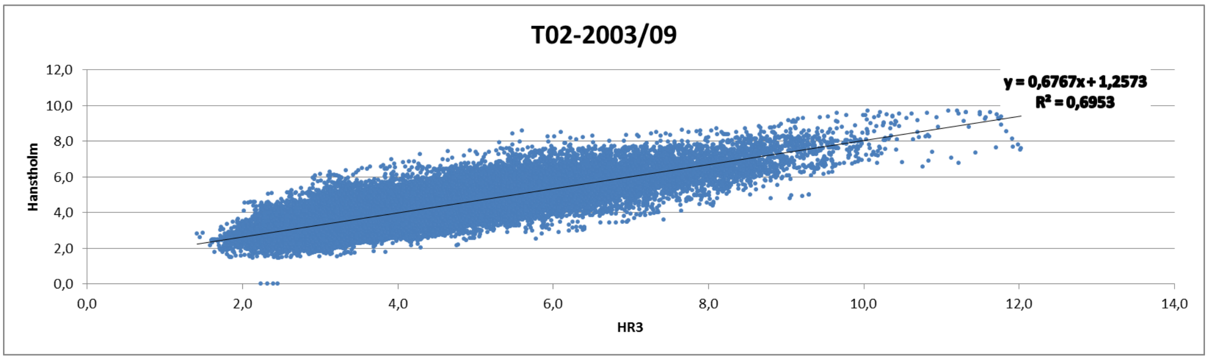
Correlation Horns Rev 3 and Hanstholm

- Dataset A: Horns Rev 3, Pt.5
- Dataset B: Hanstholm SDWED, Pt.5
- Data from 01.01.2003 at 00:00 to 31.12.2009 at 22:00

- Hm0(m):
    - Hm0_Hanstholm (m) = 0,7066*Hm0_HR3 + 0,0587
- Tp(s):
    - Tp_Hanst (s) = 0,3141*Tp_HR3 + 4,1532
- T02(s):
    - T02_Hanst (s) = 0,6767*T02_HR3 + 1,2573





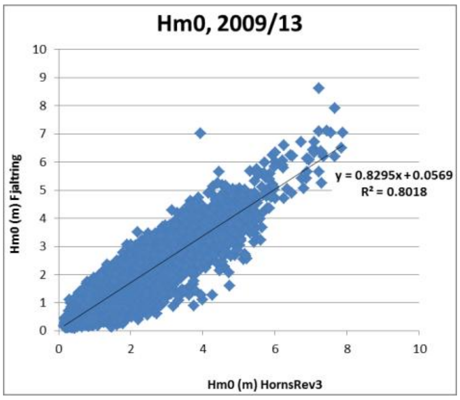


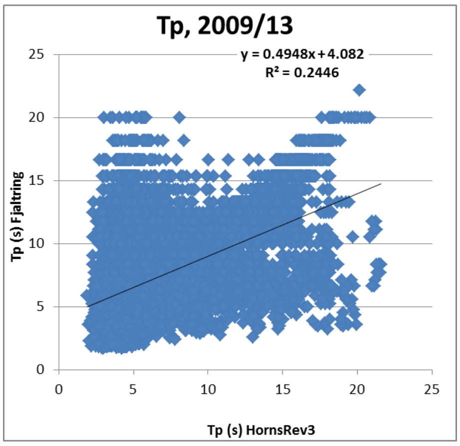
Correlation Horns Rev 3 and Fjaltring

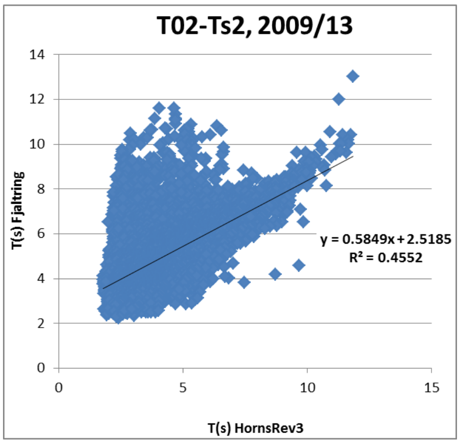
- Dataset A: Horns Rev 3, Pt.5
  - From 2003 to 2013
- Dataset B: Fjaltring Kyst
  - Data from 2009 to 03.04.2015
- Correlation from 01.01.2009 at 00,00 to 06.10.2013 at 4,30

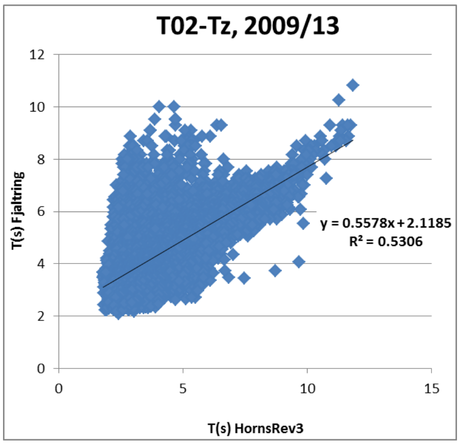
- Hm0(m):
  - Hm0_Fjaltring (m) = 0,8295*Hm0_HR3 + 0,0569

- Tp(s):
  - Tp_Fjaltring (s) = 0,4948*Tp_HR3 + 4,082









Cross-check of validity of new datapoints

Methodology:

1. Create Scatter diagram before new values are added
2. Create Scatter diagram after new values are added
3. Compare the two previous Scatter Diagrams

Hanstholm

- Scatter diagram before new values are added:

	Te(s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	
Hm0		1	2	3	4	5	6	7	8	9	10	11	12	13	14	SUM
0	0,5	0	0	21	552	664	429	217	97	67	20	12	3	0	0	2082
0,5	1	0	0	0	765	2184	1652	607	236	30	24	3	0	0	0	5501
1	1,5	0	0	0	10	1536	1502	698	287	39	14	0	0	0	0	4086
1,5	2	0	0	0	0	114	999	653	298	80	19	0	0	0	0	2163
2	2,5	0	0	0	0	1	275	662	222	31	16	3	0	0	0	1210
2,5	3	0	0	0	0	0	11	274	161	29	6	1	1	0	0	483
3	3,5	0	0	0	0	0	0	52	99	20	7	2	0	0	0	180
3,5	4	0	0	0	0	0	0	0	51	22	6	0	0	0	0	79
4	4,5	0	0	0	0	0	0	0	3	11	12	0	0	0	0	26
4,5	5	0	0	0	0	0	0	0	0	8	14	4	0	0	0	26
5	5,5	0	0	0	0	0	0	0	0	0	3	4	1	0	0	8
5,5	6	0	0	0	0	0	0	0	0	0	1	3	11	1	0	16
6	6,5	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2
6,5	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	7,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SUM	0	0	21	1327	4499	4868	3163	1454	337	142	33	17	1	0	15862

	T2(s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	
Hm0		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
0	0,5	0	0	529	1189	319	40	5	0	0	0	0	0	0	0	2082
0,5	1	0	0	226	3180	1654	403	37	1	0	0	0	0	0	0	5501
1	1,5	0	0	0	1278	2160	573	75	0	0	0	0	0	0	0	4086
1,5	2	0	0	0	19	1437	639	68	0	0	0	0	0	0	0	2163
2	2,5	0	0	0	0	377	798	35	0	0	0	0	0	0	0	1210
2,5	3	0	0	0	0	3	453	27	0	0	0	0	0	0	0	483
3	3,5	0	0	0	0	0	111	66	3	0	0	0	0	0	0	180
3,5	4	0	0	0	0	0	6	71	2	0	0	0	0	0	0	79
4	4,5	0	0	0	0	0	0	15	11	0	0	0	0	0	0	26
4,5	5	0	0	0	0	0	0	0	24	2	0	0	0	0	0	26
5	5,5	0	0	0	0	0	0	0	4	4	0	0	0	0	0	8
5,5	6	0	0	0	0	0	0	0	0	14	2	0	0	0	0	16
6	6,5	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2
6,5	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	7,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SUM	0	0	755	5666	5950	3023	399	45	22	2	0	0	0	0	15862

	T2(s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	
Hm0		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
0	0.5	0%	0%	3%	7%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.13
0.5	1	0%	0%	1%	20%	10%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0.35
1	1.5	0%	0%	0%	8%	14%	4%	0%	0%	0%	0%	0%	0%	0%	0%	0.26
1.5	2	0%	0%	0%	0%	9%	4%	0%	0%	0%	0%	0%	0%	0%	0%	0.14
2	2.5	0%	0%	0%	0%	2%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0.08
2.5	3	0%	0%	0%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0.03
3	3.5	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0.01
3.5	4	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
4	4.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
4.5	5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
5	5.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
5.5	6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
6	6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
6.5	7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0
7	7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0
	SUM	0	0	0.05	0.36	0.38	0.19	0.03	0.00	0.00	0.00	0	0	0	0	1

- Scatter diagram after new values are added:

	T2(s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	
Hm0		1	2	3	4	5	6	7	8	9	10	11	12	13	14	SUM
0	0,5	0	0	265	633	167	18	2	0	0	0	0	0	0	0	1085
0,5	1	0	0	112	1748	877	199	21	0	0	0	0	0	0	0	2957
1	1,5	0	0	0	677	1198	336	40	0	0	0	0	0	0	0	2251
1,5	2	0	0	0	7	823	425	37	0	0	0	0	0	0	0	1292
2	2,5	0	0	0	0	193	476	26	0	0	0	0	0	0	0	695
2,5	3	0	0	0	0	1	245	37	0	0	0	0	0	0	0	283
3	3,5	0	0	0	0	0	57	51	1	0	0	0	0	0	0	109
3,5	4	0	0	0	0	0	4	33	10	0	0	0	0	0	0	47
4	4,5	0	0	0	0	0	0	9	7	0	0	0	0	0	0	16
4,5	5	0	0	0	0	0	0	0	11	1	0	0	0	0	0	12
5	5,5	0	0	0	0	0	0	0	2	3	0	0	0	0	0	5
5,5	6	0	0	0	0	0	0	0	0	8	0	0	0	0	0	8
6	6,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6,5	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	7,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SUM	0	0	377	3065	3259	1760	256	31	12	0	0	0	0	0	8760

	T2(s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	
Hm0		1	2	3	4	5	6	7	8	9	10	11	12	13	14	SUM
0	0.5	0%	0%	3%	7%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.12
0.5	1	0%	0%	1%	20%	10%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0.34
1	1.5	0%	0%	0%	8%	14%	4%	0%	0%	0%	0%	0%	0%	0%	0%	0.26
1.5	2	0%	0%	0%	0%	9%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0.15
2	2.5	0%	0%	0%	0%	2%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0.08
2.5	3	0%	0%	0%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0.03
3	3.5	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0.01
3.5	4	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.01
4	4.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
4.5	5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
5	5.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
5.5	6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
6	6.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
6.5	7	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
7	7.5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00
	SUM	0	0	0.04	0.35	0.37	0.20	0.03	0.00	0.00	0	0	0	0	0	1

- Compare the two previous Scatter Diagrams
  - Can be assumed to represent the same resource

Fjaltring

- Scatter diagram before new values are added:

	Tp(s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	
Hm0		1	2	3	4	5	6	7	8	9	10	11	12	13	14	SUM
0	0.5	0	108	499	701	1302	1136	262	372	391	365	985	1112	409	274	7916
0.5	1	0	2	621	1532	3793	6859	2686	1322	629	747	2003	1964	979	910	24047
1	1.5	0	0	5	105	1301	5339	4287	3061	812	435	856	700	275	174	17350
1.5	2	0	0	0	0	44	1557	3087	3532	1252	593	420	264	78	31	10858
2	2.5	0	0	0	0	0	178	1009	2651	1116	612	393	111	29	15	6114
2.5	3	0	0	0	0	0	5	186	1366	898	567	417	87	18	8	3552
3	3.5	0	0	0	0	0	0	11	305	488	397	432	82	10	5	1730
3.5	4	0	0	0	0	0	0	0	29	141	214	353	78	6	3	824
4	4.5	0	0	0	0	0	0	0	1	18	44	173	68	8	2	314
4.5	5	0	0	0	0	0	0	0	0	2	1	50	49	13	8	123
5	5.5	0	0	0	0	0	0	0	0	0	0	9	16	12	7	44
5.5	6	0	0	0	0	0	0	0	0	0	0	2	10	8	8	28
6	6.5	0	0	0	0	0	0	0	0	0	0	1	3	3	9	16
6.5	7	0	0	0	0	0	0	0	0	0	0	0	1	0	3	4
7	7.5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
	SUM	0	110	1125	2338	6440	15074	11528	12639	5747	3975	6094	4545	1849	1457	72921

Conclusions

- Correlation between wave parameters of HornsRev3 and Hanstholm:
  - For H_{m0} is high (R^2=0.76)
  - Very low for T_p (R^2=0.21)
  - High for T_{02} (R^2=0.7)
    - Therefore H_{m0} and T_{02} have been selected
    - Next step, deriving Pprod. of Wavestar at Hanstholm, and at HR3, as a function of H_{m0} and T_{02}.

- Hanstholm lacks about 90% of data for 2013. Hanstholm Scatter Diagrams, before and after filling in with missing data, look alike --> methodology approved

Cross-correlation and average delay between HR3 and Hanstholm waves

Definition

The relationship between two different parameters can be evaluated by the Cross-Correlation coefficient.

The cross-correlation coefficient indicates the extent to which two things are related to each other, i.e. the degree to which the variation in one parameter, *x*, is reflected in the variation of the other parameter, *y*.

The cross-correlation coefficient varies in the interval [-1, 1], where:

- A value of <-1> indicates perfect negative correlation.
- A value of <0> indicates no correlation.
- A value of <-1> indicates perfect positive correlation.

It is important not to confuse the cross-correlation coefficient with the "determination coefficient" (R^2), also widely used. While the correlation coefficient varies in the interval $-1<CC<1$, the determination coefficient has a varying range of $0<R^2<1$.

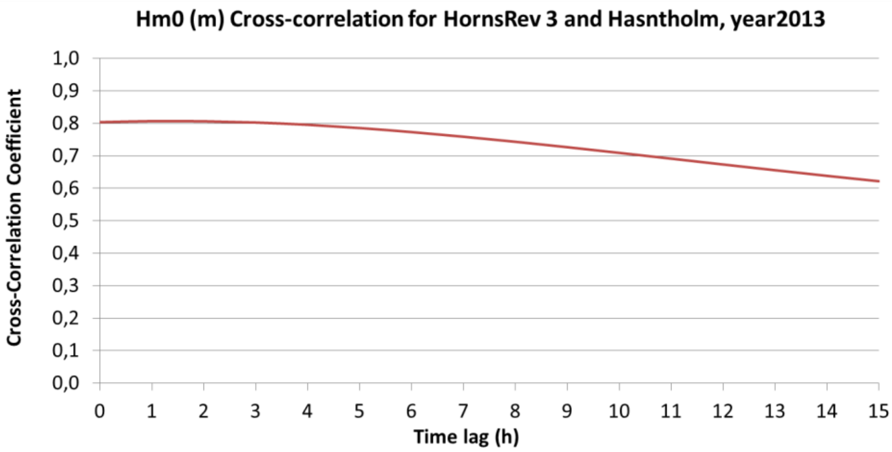
The time lag at which the correlation reaches a maximum is defined as the average delay (Fusco, et al., 2010)[10]. It is defined as:

$$Cross - Correlation\ (t) = \frac{1}{N}\sum_{k=1}^{N-t}\frac{[(x(k) - \mu_x)\ (y(k+t) - \mu_y)]}{\sigma_x\ \sigma_y}$$

The cross-correlation coefficient is a function of a time lag *t,* which reflects the temporal relationship between two variables, *x* and *y*. *k* is a counter indicating time, *N* is the number of samples, μ the sample mean and σ the standard deviation.

Calculations

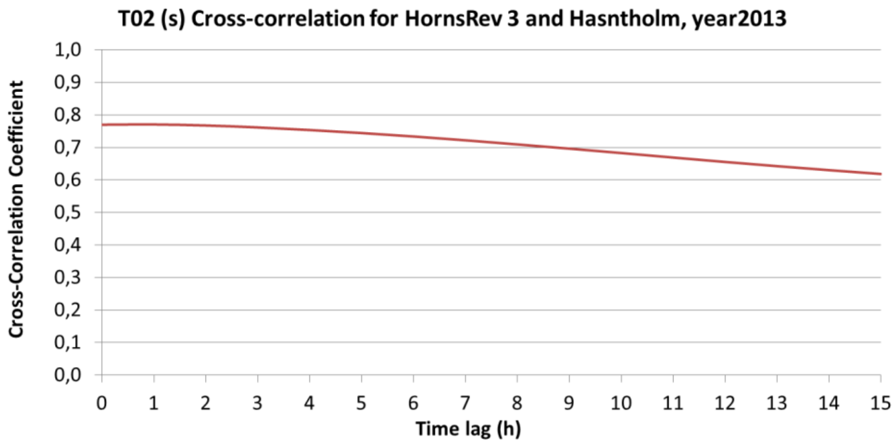
Figures below investigate the cross-correlation coefficient between wave parameters in Horns Rev 3 and in Hanstholm. Parameters investigated are: H_{m0}, T_{02}, $H_{m0}^2 * T_{02}$ and $H_{m0}^{2.5}$, respectively. Study year is 2013.



This cross-correlation coefficient is aligned with the correlation result provided before (in Section "Correlation Horns Rev 3 and Hanstholm"):

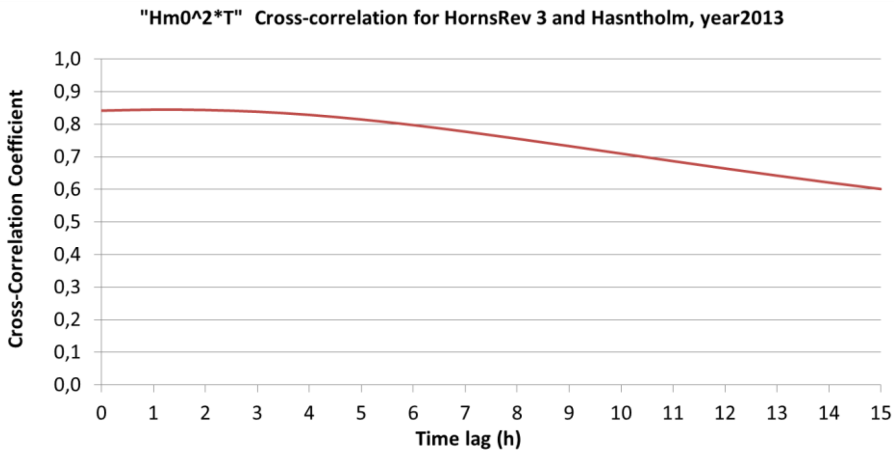
- $R^2=0.7565$ ==> CC (t=0)=0.87

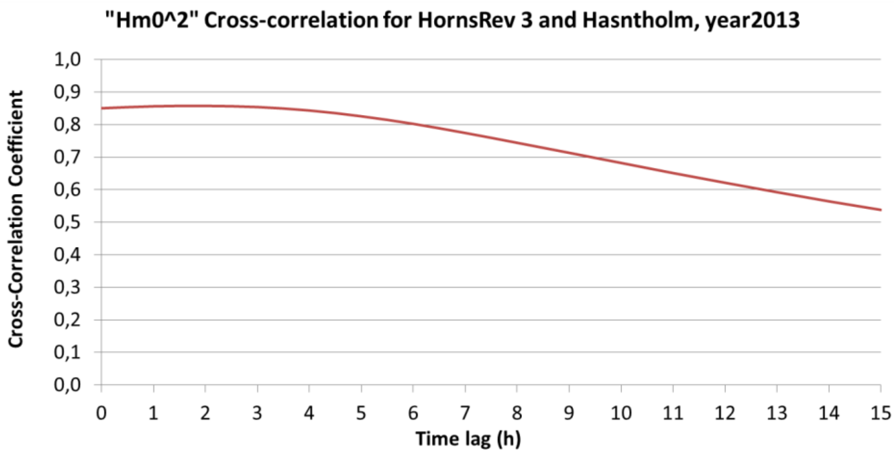
[10] Fusco, F, Nolan, G and Ringwood, JV. "Variability reduction through optimal combination of wind/wave resources - An Irish case study". Energy 35, 2010, pp. 314-325.



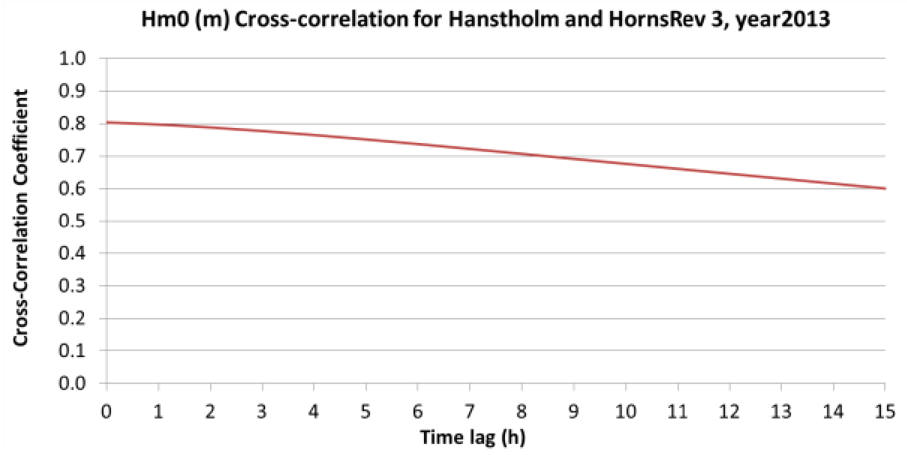
This cross-correlation coefficient is aligned with the correlation result provided before (in Section “Correlation Horns Rev 3 and Hanstholm”):

- R^2=0.6953 ==> CC (t=0)=0.83





For comparison, below is provided the Cross-Correlation and average delay of waves “moving” from Hanstholm to Horns Rev 3 (opposite direction as in the previously shown). Results prove not to be the case:



*Note: calculations can be found at '*Cross-Correlation (HR3-Hanst.).xlsx*'

Conclusions:

Calculations on the average delay between waves in Horns Rev3 and Hanstholm, by comparing the following parameters H_{m0}, T_{02}, $H_{m0}^{2}*T_{02}$ and $H_{m0}^{2.5}$, indicate that:

- The cross-correlation between wave parameters in HornsRev 3 and Hanstholm is relatively high, around 0.8 (CC coefficient varies from 0 to 1)
- There is an average delay of 1 to 2 hours between the conditions in Horns Rev 3 and Hanstholm

CC(t=0) and Time lag in hours when CC is max.	H_{m0}(m) at Hanstholm	T_{02}(s) at Hanstholm	H_{m0}^{2} * T at Hanstholm	$H_{m0}^{2.5}$ at Hanstholm
H_{m0}(m) at HR3	CC(t=0)=0.80 t=1-2h (CC=0.81)	-	-	-
T_{02}(s) at HR3	-	CC(t=0)=0.77 t=1h (CC=0.77)	-	-
H_{m0}^{2} * T at HR3	-	-	CC(t=0)=0.84 t=1-2h (CC=0.84)	-
$H_{m0}^{2.5}$ at HR3	-	-		CC(t=0)=0.85 t=2h (CC=0.86)

From wave parameters (H and T) to wave production

- WECs Power production is calculated at each location
- H and T are input values, transfer function is WEC's power matrix, and output values is the hourly power production

    - WEC selected: Wavestar[11, 12]
        - Prons:
            - Project partner
            - 4-year experience in testing and operating in Danish waters
            - Power matrix designed for a Wavestar operating in the Danish North Sea
        - Cons:
            - Stops production when $H_{m0} \geq 5$ m (on the other hand WECs will normally have an upper operational limit, forced by a limit in their installed capacity and their storm strategy)

    - Alternative WECs to select:
        - Wave Dragon[13, 14], but there is no power matrix available representing / suitable for Danish conditions (at least not yet).
        - Weptos[15, 16], but lacks operation experience in North Sea, and thus the power matrix might not be as realistic as Wavestar power matrix.

Input: wave parameters

- HR3: H_{m0}, T_{01}, T_{02} and T_p
- Hanstholm: H_{m0} and T_{02}

Relationship among wave parameters

- *Ratios T_e / T_{m01} and Peak Period (T_p) / T_{m01}* ([17])
- $T_e = 1.055\ T_{m01}$
- $T_p = 1.2\ T_{m01}$

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[11] Kramer, M.M., Vidal, E., Marquis, L. and Frigaard, P. "Status and perspectives for the Wavestar demonstrator at Hanstholm", in Proceedings of the 10th European Wave and Tidal Energy Conference (EWTEC´13), Aalborg, 2013.

[12] Kramer M., Marquis L., and Frigaard P. "Performance Evaluation of the Wavestar Prototype", in Proceedings of the 9th European Wave and Tidal Energy Conference (EWTEC). Southampton, 2011.

[13] Tedd , J.; Kofoed , J.P.; Knapp, W.; Friis-Madsen, E.; Sørensen, H.C., "Wave Dragon, prototype wave power production". World Renewable Energy Congress, Florence, 2006.

[14] Soerensen H.C and Friis-Madsen E. "Wave Dragon from Demonstration to Market" in Proceedings of the 3rd International Conference on Ocean Energy, Bilbao, 2010.

[15] Pecher A., Kofoed J.P. and Larsen T. "Design Specifications for the Hanstholm WEPTOS Wave energy Converter", Energies 2012, 5, 1001-1017; doi:10.3390/en5041001, 2012.

[16] Pecher A., Kofoed J.P. and Larsen T. "The extensive R&D behind the Weptos WEC". RENEW Conference, Lisbon, 2014.

[17] Aina Figueras-Álvarez, "Estimation of available wave power in the near shore area around Hanstholm Harbor", Civil Eng. Department, Aalborg University, 2009.

Wavestar power matrix

Old power matrices

Old Power matrix I:

- Dated from oct. 2012
- Wave Star C5 600 kW machine with 20 floats (based on Numerical calculations)
- Float diameter 6 m
- Defined in terms of H_{m0} and T_{02}
- Power production starts at H_{m0}=0.5m and stops at H_{m0}=4m

Old Power matrix II:

- Dated from oct. 2012
- Wave Star C5 600 kW machine with 20 floats (based on Numerical calculations)
- Float diameter 5 m, water depth 10 m
- Defined in terms of H_{m0} and T_{02}
- Power production starts at H_{m0}=0.5m and stops at H_{m0}=3m

New power matrix

> *[correspondance with Wavestar, Maj2015] "Since I don't expect that the wave climate in Denmark will change significantly in the next 20 years, it is safe to assume that the probability for Hs > 3[m] is below 1% and therefore the greyed out cells are not relevant. The power matrices follow the same format as those you have from oct. 2012"*

- Dated from May 2015
- File titled: 'Power matrices WSE-2035'
- Defined in terms of H_{m0} and T_{02}
- Power matrix assumes.
    - 100% operation
    - Array interaction
    - Power limit and
    - Storm protection limit
- Power production starts at H_{m0}=0.5m
- Power production stops at H_{m0}=4m
- **Power matrix 1, PM1**: Wave Star 1500 kW machine with 20 floats, 6 meter float diameter
- **Power matrix 2, PM2**: Wave Star 800 kW machine with 20 floats, 5 meter float diameter (also available. Power production stops at H_{m0}=3m)

POWER MATRIX I

Machine (20 floats Ø=5[m]): Electrical power [kW] — 100% operation, array interaction, power limit and storm protection limit

Hm0 range [m]	Hm0 [m]	Wave period T0,2 [s]															
		0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16
		0,5	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5
0.0 - 0.5	0,25	0	0	0	0	11	14	16	17	17	16	16	15	14	13	13	12
0.5 - 1.0	0,75	0	0	21	57	94	109	108	103	95	88	82	77	72	68	64	61
1.0 - 1.5	1,25	0	0	57	158	234	243	230	210	191	175	161	150	140	131	124	117
1.5 - 2.0	1,75	0	14	112	308	406	400	366	328	296	269	247	228	213	199	188	177
2.0 - 2.5	2,25	0	24	185	488	601	571	512	456	408	370	338	312	290	271	255	240
2.5 - 3.0	2,75	0	35	276	705	800	753	667	591	526	475	433	398	370	345	325	306
3.0 - 3.5	3,25	0	49	385	800	800	800	800	732	649	584	532	488	453	422	396	373
3.5 - 4.0	3,75	0	66	513	800	800	800	800	800	777	698	633	580	538	501	470	442
4.0 - 4.5	4,25	0	85	659	800	800	800	800	800	800	800	736	674	624	581	545	512
4.5 -	4,75	0	106	800	800	800	800	800	800	800	800	800	770	712	662	621	582

POWER MATRIX II

Machine (20 floats Ø=6[m]): Electrical power [kW] — 100% operation, array interaction, power limit and storm protection limit

Hm0 range [m]	Hm0 [m]	Wave period T0,2 [s]															
		0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16
		0,5	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5
0.0 - 0.5	0,25	0	0	0	12	20	26	26	30	31	31	30	30	28	27	25	24
0.5 - 1.0	0,75	0	0	24	68	117	150	161	159	151	142	132	124	117	110	104	99
1.0 - 1.5	1,25	0	0	64	177	288	344	348	331	307	282	261	243	227	214	202	191
1.5 - 2.0	1,75	0	17	122	336	515	581	566	525	479	438	402	373	348	327	307	291
2.0 - 2.5	2,25	0	27	199	539	785	849	805	734	664	603	552	511	475	445	419	396
2.5 - 3.0	2,75	0	41	295	776	1087	1139	1060	956	860	778	711	656	608	569	534	504
3.0 - 3.5	3,25	0	57	411	1059	1424	1448	1328	1190	1066	961	876	805	746	697	654	617
3.5 - 4.0	3,75	0	76	549	1367	1500	1500	1500	1434	1280	1151	1046	960	888	829	777	733
4.0 - 4.5	4,25	0	97	705	1500	1500	1500	1500	1500	1500	1346	1222	1119	1034	964	903	851
4.5 -	4,75	0	121	879	1500	1500	1500	1500	1500	1500	1500	1401	1280	1182	1101	1031	971

From wave timeseries (H and T) to wave production

From wave timeseries (of Hanstholm and Horns Rev 3), defined in terms of H_{m0} and T_{02}, to power production. The challenge: to interpolate / calculate for the correct (H, T) among the given intervals of the power matrix.

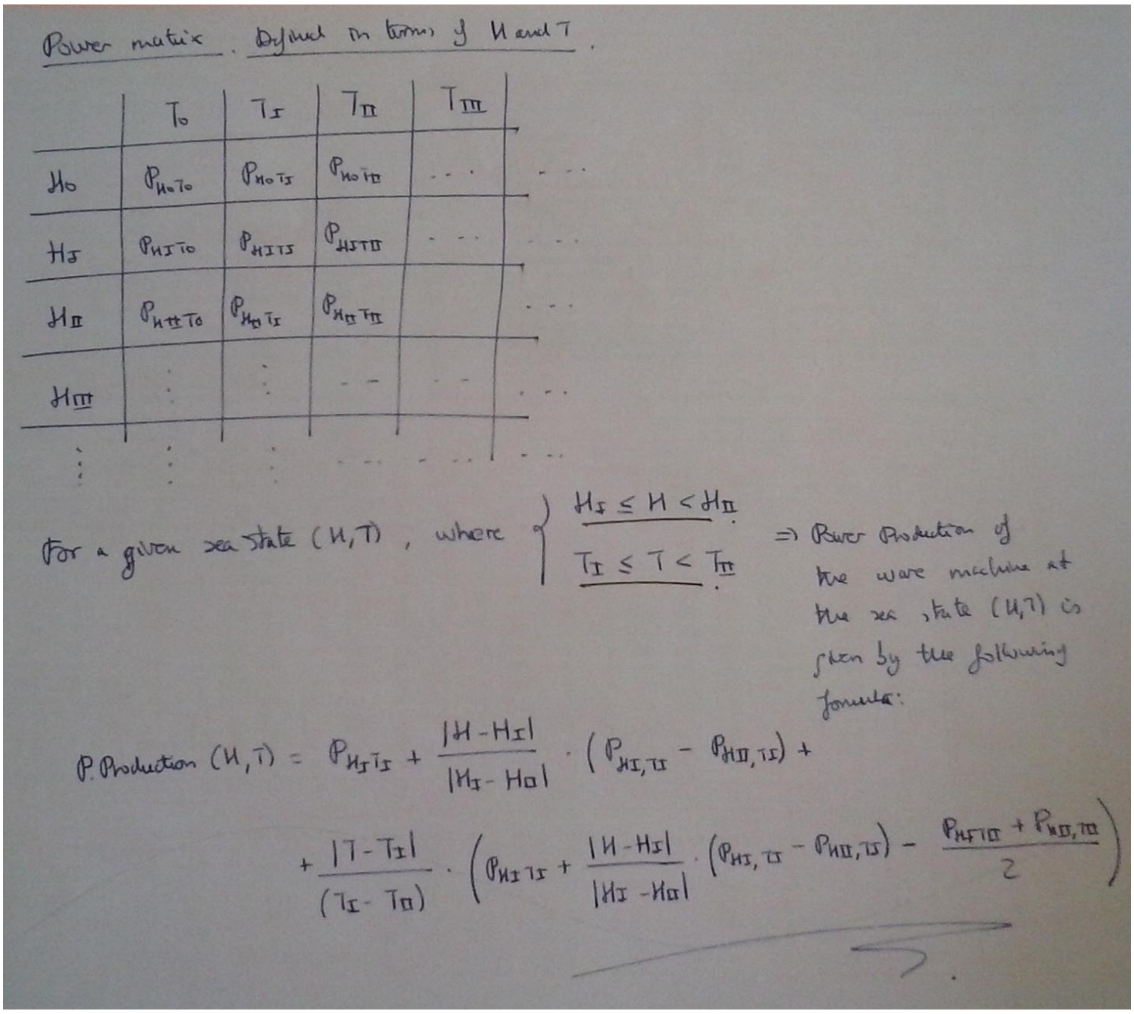
A power matrix provides the expected power production (in kW or in non-dimensional units: kW/kW) of a WEC normally in terms of H_{m0} and T_{02}. The wave climate of Hanstholm and Horns Rev 3 during the study period (year 2013) is defined by a time-series of sea states, hourly values of H_{m0} and T_{02}.

Wavestar power production of has been obtained with the power matrix, for the bin (H_{m0}, T_{02}) corresponding to the hourly wave condition measured at the site.

Whenever the occurring sea state does not coincide with the intervals the power matrix is defined, power productions are interpolated (i.e. a weighted average calculation) among the closest upper bin values, for both H_{m0} and T_{02} and the closest lower bin values, also for H_{m0} and T_{02}. A weighted average of all these four values (power productions) results in the expected Wavestar power production at that sea state.

A calculation tool based on this methodology has been developed. It provides the expected power production for a given sea state (H, T) based on two inputs: a given power matrix, and a given timeseries of wave parameters.

Calculation steps are shown below:

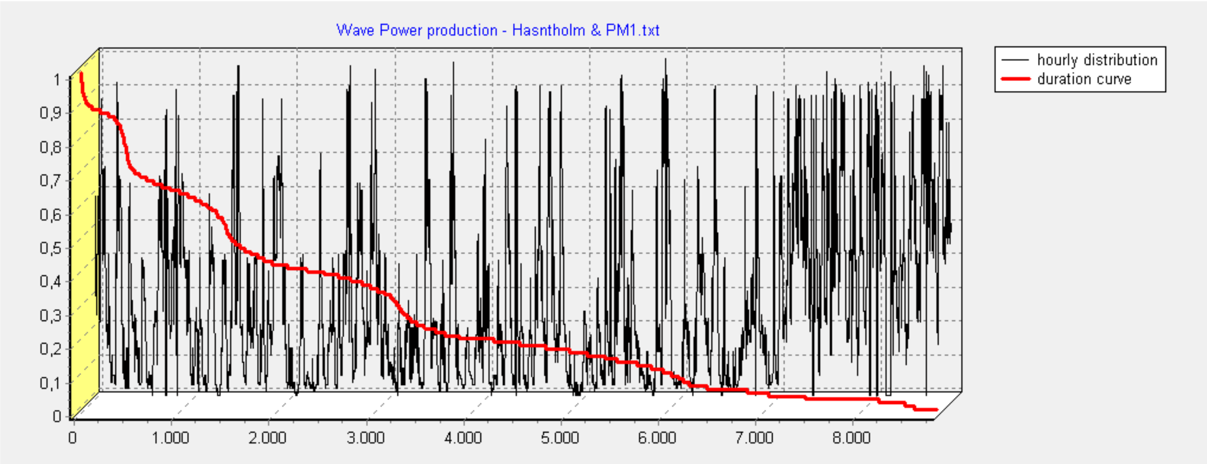


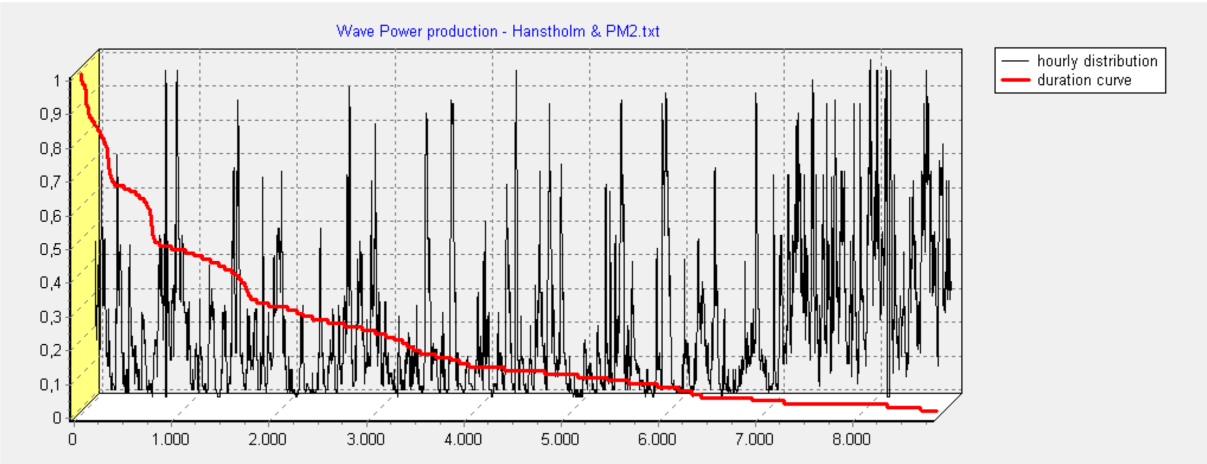
If power productions of WECs were not calculated as weighted averages but by taking the closest value from the power matrix, this would result into power productions varying in steps.

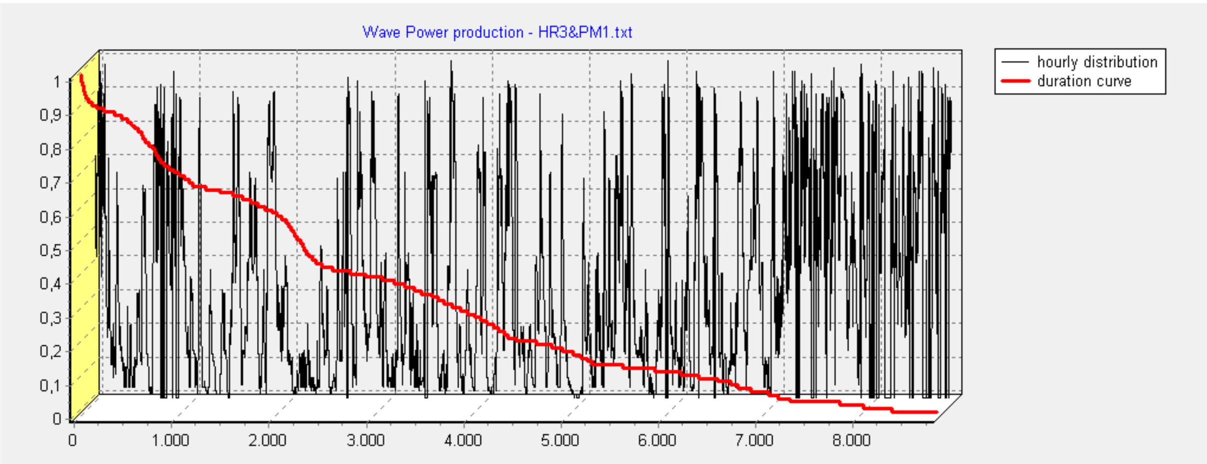
Comparison of Wavestar Power Production, for 2 power matrices and at 2 locations

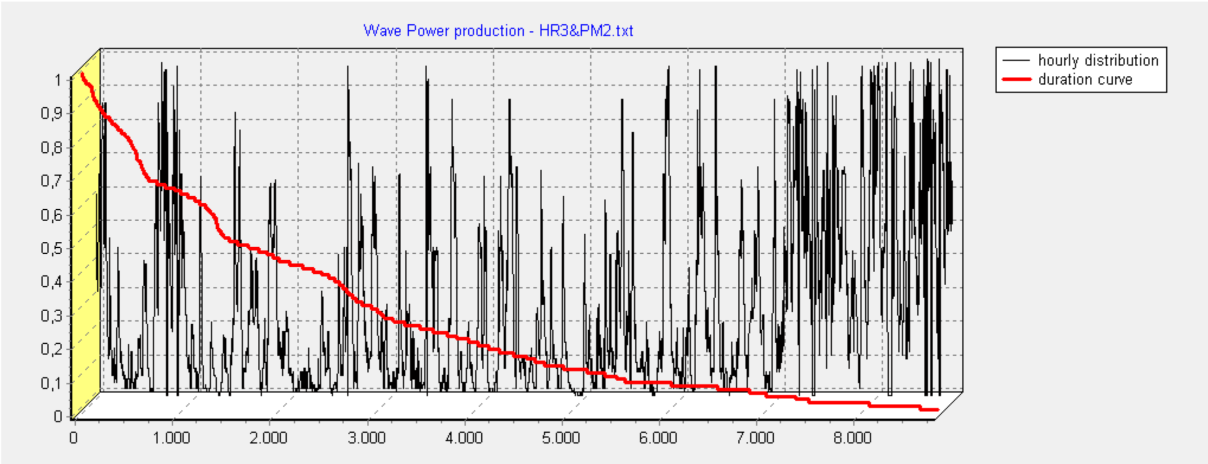
	Capacity	Total Production	Capacity Factor	Max. Production	h/year with Prod=0 kW		Average Value
	kW	MWh	%	kWh	h/y	%	p.u.
HR3 & PM2	1500	3361	26%	1468	160	2%	0,26
HR3 & PM1	800	2069	30%	745	452	5%	0,32
Hansth. & PM2	1500	2665	20%	1480	149	2%	0,21
Hansth. & PM1	800	1813	26%	749	230	3%	0,28

Duration curves of each file are represented below:





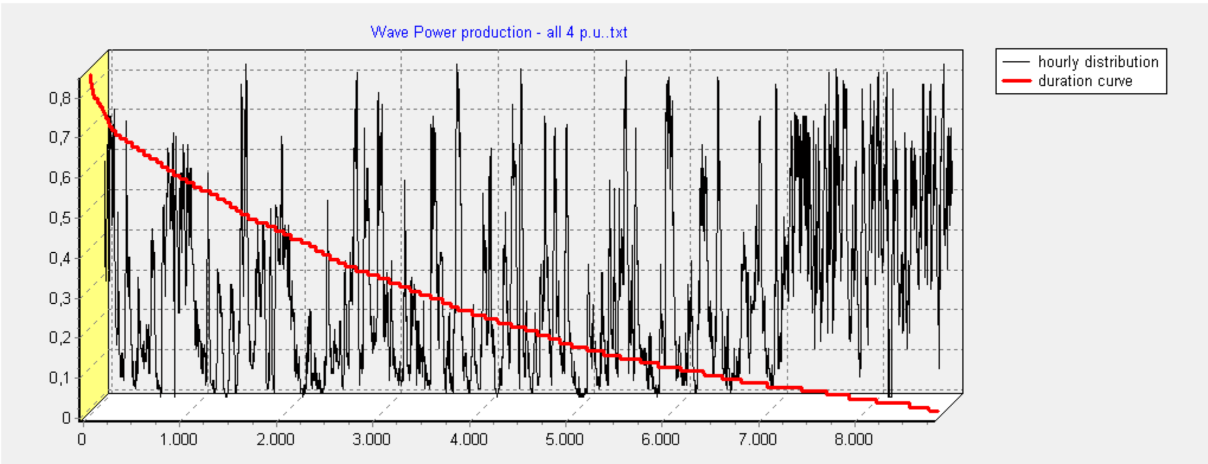




Combined Wavestar Power Production: of the 2 power matrices and at the 2 locations

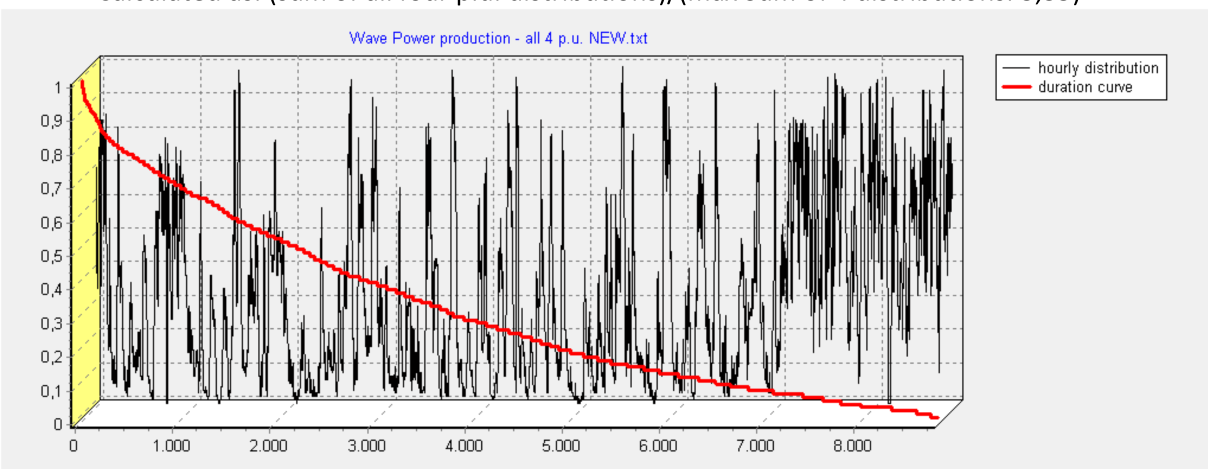
Methodology I

- Calculated as: (sum of all four p.u. distributions)/4



Methodology II

- Calculated as: (sum of all four p.u. distributions)/(max Sum of 4 distributions: 3,35)



Methodology III

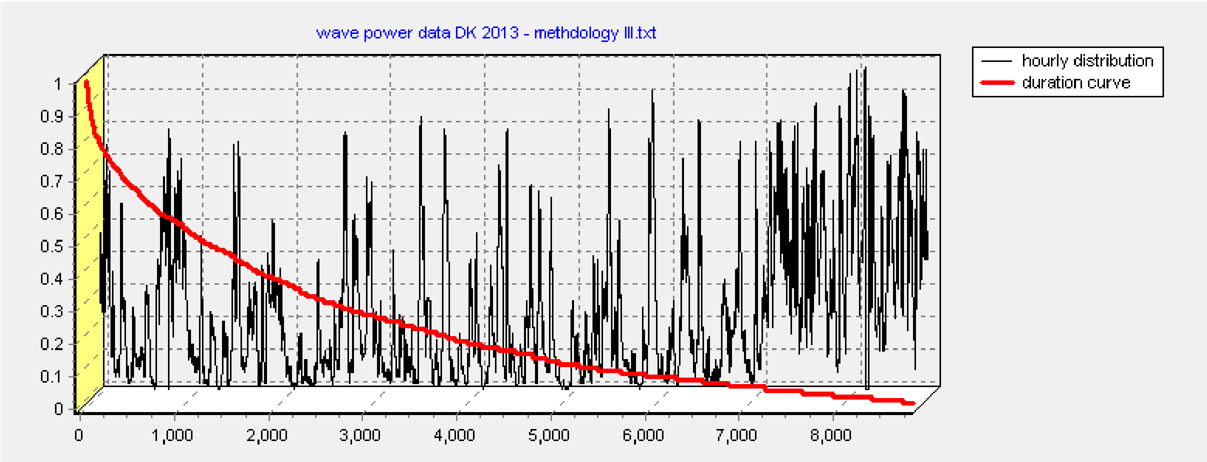
Provided:

- An average delay of 2 hours between waves at HR3 and Hanstholm
- We aim to represent the accumulated wave power production in the Danish North Sea

The calculation approach is the following:

- The machines are placed in the time slots 0h, 1h and 2h.
- 0h corresponds to the HR3 location and the estimated production is based on Wavestar Power Matrix 2
- 2h corresponds to the Hanstholm location and the estimated production is based on Wavestar Power Matrix 2
- 1h is somewhere in between and the estimated production is based on the weigthed average of the power production at HR3 and Hanstholm with Wavestar Power Matrix 2.

*(*Calculations in file: "Wave P.Prod. 2013 Combined")*



Summary of the three methods

		Max. Production	h/year with Prod=0 kW		Average Value
		p.u.	h/y	%	p.u.
Method I	**p.u. / 4**	0.84	45	1%	0.27
Method II	**p.u. / max sum(4)**	1	45	1%	0.32
Method III	**0h,1h,2h delay**	1	39	0%	0.24

Methodology II provides the higher capacity factor of the three methods, closer to international projections of the Cf of wave energy. Also, sensitivity analyses comparing the different files have been carried out, indicating minor differences between the results achieved using one file or another. The chosen final file is based on Methodology II.

Conclusions:

Distribution Files to be included in EnergyPLAN model

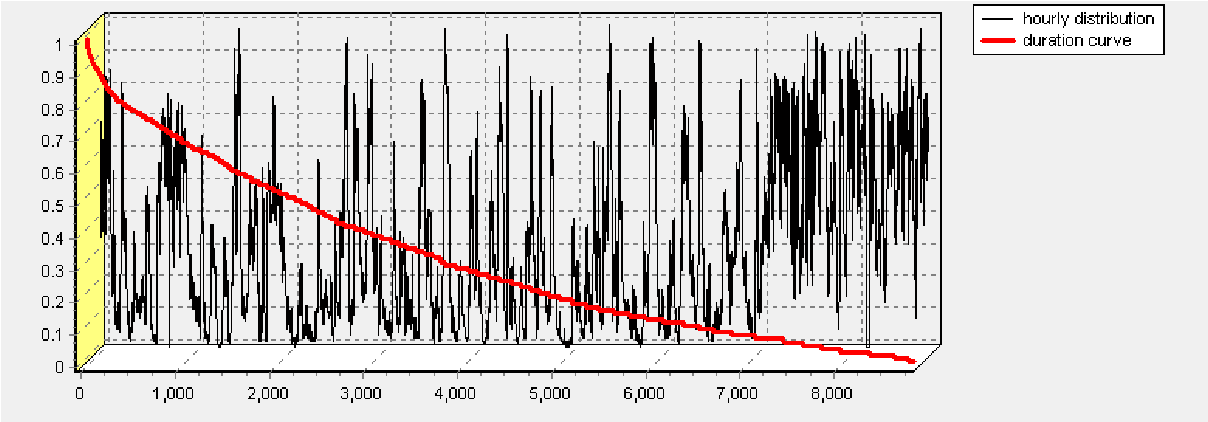
The EnergyPLAN model takes as input per unit hourly power production. Files are 8784 hours long. Since 2013 has 365 days, the last 24 hours of the year are repeated in order to reach 8784 hours.

The following files have been created:

The files below represent the power production of Wavestar (with power matrix 1 and with power matrix 2, respectively) at the indicated location:

- '*Wave Power production - Hanstholm & PM2*'
- '*Wave Power production - Hanstholm & PM1*'
- '*Wave Power production – HR3 & PM2*'
- '*Wave Power production – HR3 & PM1*'

Final distribution file representing Danish wave conditions has been called '*wave power production Danish North Sea 2013*', and its duration curve and pattern over year 2013 is represented below:



Recommnedations for Further Work

It is suggested to improve the distribution data for wave power by adding a third point to the calculations. The final wave data file is based on wave measurements at two nearshore locations of the Danish Northe Sea, Horns Rev 3 and Hanstholm. If wave data from an offshore location like Ekofisk is available, also for year 2013, the distribution file for wave production will be more representative of the contribution that wave power can provide to the Danish system, as geographical dispersion would be taken into account in the distribution file.

Also, data can be improved by adding distribution data from other years, in order to take into account yearly variability of renewable energy sources.

Quality Control of Hanstholm half-hour wave data for year 2013

It looks generally OK although there are lot of data missing or data that appears twice:

- The most common missing hours in general correspond to: 0:00. 0:30, 9:00. 9:30 and 10:00 along the whole year

- There are missing days in January, May, June and October
  - From 01.01, 00 to 09.01, 9:30
  - From 21/5/13 at 9 to 24/5/13 at 9
  - From 6/6/13 @ 00 to 13/6/13 @ 13
  - From 24/10/13 @ 7 till 6/11/13 @9:30
  - From 31.12 @ 00 till 31.12. @23.00

- From May the number of mistakes arises and hours start to be repeated

- June and July have the greatest number of hours repeated

- From August the hours repeated decrease and the mentioned missing hours (bullet 1) appear again

Quality Control of Fjaltring half-hour wave data for year 2013

Along the whole year the same kind of bugs can be found. These are: hours missing.

- The hours missing are spread randomly along the different days of the different months.

- Having identified months with less number of hours missing than others, in general all of them have a big amount of missing hours.

- Moreover, the dataset for year 2013 does not cover the whole 2013 as data is missing from October 6th onwards.

Annex V. Additional Databases for Wind, Wave and Solar PV data

Date: April 2015
Authors: Julia F. Chozas

Wind and Wave

- DONG:
    - Vi har Hindcast data med både vin dog bølger fra forskellige områder ved Horns rev.
    - Vi har noget ældre fra 2006 (HR2) og noget sprit nyt til Horns rev 3. Som jeg lige husker det har vi i begge datasæt omkring 20 års data.
    - Anders sidder med det i øjeblikket da han arbejder med HR3.
    - Lad os tage det fra HR2. Dels fordi det er det de har spurgt efter, og dels fordi det formentlig er mindst følsomt i forhold til den kommende tender. Har vi flere HR2 positioner, så tag den dybeste.

- Energi Styrelsen:
    - Gives access Database of all wind turbines in DK, with yearly production data, from 1977: http://www.ens.dk/info/tal-kort/statistik-noegletal/oversigt-energisektoren/stamdataregister-vindmoller
    - Map of wind turbines in DK: http://vindinfo.dk/kort.aspx

- Horns Rev 3 hindcast-data: http://www.energinet.dk/DA/ANLAEG-OG-PROJEKTER/Anlaegsprojekter-el/Havmoelleparken-Horns-Rev-3/Forundersoegelser/Sider/Datapakker.aspx
    - Hindcast data developed by DMI: 1. jan 2003 - 1. maj 2013 (10 år og 4 måneder).
    - Tidsopløsningen er 1 time.
    - Also access to raw data for 1999-2004
    - Waves at HR3 are better than at HR2, less disturbed (deeper waters)

- Production data for the Avedøre 2 turbine can be found here: http://hvidovrevind.com/

- Contact person for the data from FINO2 and FINO3 is Olaf Outzen:Olaf.Outzen@bsh.de

- Anholt data:
    - DHI Hindcast data from 1979 to 2007
    - Wind and wave data
    - "Please note the note in the dataset top, and please return an email where you state that you will not distribute these, and that you will comply with the notes at the start of the file"
    - There are also wind measurements at the harbour, at H=10m – Pb: when extrapolated to hub height (80meters) they are much higher
    - Also raw wind data available from liadars (raw data, has to be treated)

- Leo has sent a Generic wind turbine Power curve.

- "Unfortunately, we cannot provide you with measured wind data for Horns Rev or Anholt for the period 2012-2013. Instead, please consider using the power curve provided by Leo together with the measured wind data from either the nearby FINO3 platform, or from a measurement station onshore. For the latter, you can try to contact Carsten Kofoed.

- Data Horns Rev2 from Morten Kramer (AAU and WS):
    - 1979 to 2003

  - 30 min resolution
  - Wind and wave
  - Note! Problem at HR2: waves are worst than in HR3

- http://kysterne.kyst.dk/

- DMI:
  - Jacob Woge Nielsen, Quotation: 12000 DKK for 2years hourly data of Hm0, T02, u and direction. Wherever in the North Sea.
  - Ask him from a measurement station onshore data of Anholt - Carsten Kofoed from DHI (Carsten Kofoed cnk@dmi.dk) - tell him I´ve got his contact from Anders, although I´m not DONG.

- Energinet.dk. Data regarding Metocean and wind resource studies on Horns Rev 3 Offshore Wind Farm, ftp2.energinet.dk

Wave

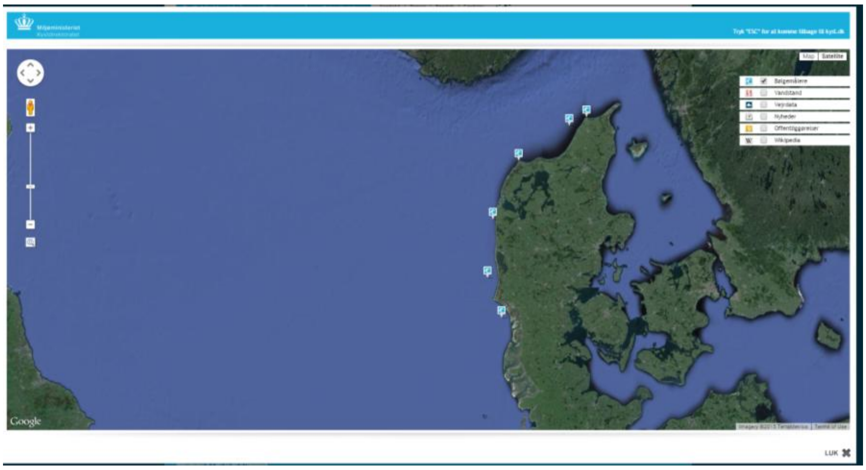
Other wave data sources for year 2013

I. Ask Universidad de Cantabria for wave data (or Other suggestions on the sources from where we could get more data for year 2013?)

II. Fjaltring
  - Calculate missing H and T, then Calculate Pprod → 8744 data points

III. From Kyst.dk:
  - Fanø,
  - Nymindegab,
  - Hirtshals W,
  - Hirtshals Havn (maybe not from this one – might be in too shallow waters?)

    - Hirtshals:
      - half-hourly data,
      - from 2009 to 2012-08-29. Can we get data for Year 2013?
      - Data point Hirsthals W:
        - Ident 1041: 524 559 E 6 381 744 N vanddybden er ca. 17 m.



IV. Alternatively: search for wave data for other years with similar Wind Index as year 2013 - Based on knowledge about the wind index of year 2013 (it has been a low-to-average wind year); we can look for a year with the same characteristics, where data from pt.1

exists (i.e. pt.1 of Hanstholm, from modelled DHI data), and assume it is a representative year.

Solar PV

- Estimation of daily and yearly solar PV energy for Europe (pick a place): http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#
- http://energinet.dk/DA/El/Engrosmarked/Udtraek-af-markedsdata/Sider/Femminutters-maalinger.aspx (data from Energinet)
- http://clxportal.danfoss.com/da_DK/PlantList (data from Danfoss inverters)
- www.rmi.org (Reinventing Fire)
- http://www.navigantresearch.com/research/solar-pv-market-forecasts (might be costly)
- http://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/study-levelized-cost-of-electricity-renewable-energies.pdf (LCOE for renewables)

- http://www.solarforecasting.nl/

- Remus Teodorescu (AAU) might have Irradiation Data

- Data Århus paper comes from a model WEPROG (DK & DE company), hourly model, data 2001-2007, 50x50 km^2 resolution.

- Søren:
    - Irradiation data measured at Brædstrup:
        - from 2004 to 2007;
        - no temperature measurement
        - They have checked there 7 inverters?
    - PVSYST: synthesise output power and Temp.
    - INSEL (1 month free trial)
    - Excel file
        - Name: 'Data to be used external - 01a SBK 2013-09-16'
        - Data er ikke fra ét år, men er fremstillet syntetisk.
        - Jeg tror, at data er gældende for København.
        - Dette er én af grundene til, at jeg mener du bør bruge de rigtige data, og ikke kun disse syntetiske data.
        - For forbrugsdata betyder median, at jeg har brugt en median funktion på de 46 datasæt

- DONG: Knud and Claus
    - Extract of 20 plants (net settlement group 2 + 4):
    - Hourly values from plant commissioning fixing date (April-May 2013) up to date (17/03/2014).
        - i.e. from 01/04/2013, 00:00 to (17/03/2014 @13:00)
    - The extract is applied to the DEF industry code and postal code.
    - Data fields:

        1) Fra Net eg Consumption - Til Net eq Production
        2) Time is Danish Time - with the Time Stamp 01:00 covering Data from 00:00 to 01:00 etc.
        3) Værdi is in kWh - and is the avg. value for the hour
        4) The Time Stamp 03/05/2013 03:00 covers Data from 03/05/2013 02:00 - 03:00

5) Installed capacity (kWp) of each of the units
→ 25 numbered houses in total, houses 12, 16,17,19,21 are missing.
- "I don't have the data that I have sent you - however I think that you are right - the data in Column 1 are hourly production from M3 - there aren't a M1 Meter installed to measure the sole production from the Solar Panels"

- Alternatively, get solar PV data from individuals:
  - Søren:
    - Installed power: 10 kW
    - Panel inclination: 30°
    - Azimuth:
    - Inverter type
    - Operation starting time:
  - JPK:
    - Installed power: 6.2 kW (33 panels, 190 W each)
    - Panel inclination: 45°
    - Azimuth: 13° towards East
    - Inverter type: 3-phase inverter, 8 kW (limited to peak power of 6.2 kW)
    - Operation starting time: from May 2012 onwards
      → www.monitoring.solaredge.com
  - HCS

- Solar polymer PV: http://plasticphotovoltaics.org/contact-page.html

- Data from Energinet.dk - Rasmus Munch Sørensen [RMS@energinet.dk], March 2015
  - Installed capacity (MW) from 18dec2013 till now
  - Production for 2014
  - Production for year 2013:
    - Unfortunately we do not have reliable production data for all of 2013. I've attached what he sent me, but with his own words, the data are not reliable for the first half of '13, and thus should probably be disregarded.
    - We have not made any projections of production based on the capacity, but given the data provided you might be able to do that.

Others

Gorm Andersen – Solar PV and Renewable energy atlas
- Solar300 Project – Energinet.dk (Jeanette?)
- ISET(IWES) Fraunhofer
- RE ATLAS, global dataset, 1979 to 2013; 40*40 km^2; 1h resolution

- Models Gorm: RE atlas ; solar PV data, Sol300.
  - http://globalatlas.irena.org/
  - http://maps.nrel.gov/re_atlas
  - http://en.openei.org/wiki/RE_Atlas
  - The PV project is called sol 300. some info: http://www.managenergy.net/resources/192
  - I'll send you info in the atlas. It has not been published yet.

Energinet
- Link http://www2.emd.dk/el/ Det viser den reelle elproduktion fra vind og kraftværker samt forbrug på 5mins basis. Derudover er der også spot- og op- og nedreguleringspriser. For nylig

er sol også blevet inkluderet men det er ikke den reelle produktion da vi ikke har adgang til den data pga. nettomålerordningen. Men det er så vidt jeg husker baseret på data fra mange (måske 1000) rigtige solcelleanlæg i Danmark, så det er et rimeligt godt bud.

- http://energinet.dk/DA/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx
    - Produktion fra vind og sol på timebasis for hhv. DK øst og DK vest.
    - We may also provide access to data at 5-minute basis also divided into DK east and west, but that's as far as I know minute power values and not average production.

Annex VI. Capacity Credit Definitions

This Annex provides more definitions of the parameter capacity credit, all having the same meaning as the definition given in Chapters II and IV.

- Capacity credit represents the amount of power (as an average output of the plant) that the TSO expects, on average, to be available.

- Capacity credit represents the reliable capacity available at times of peak demand.

- The capacity credit is the amount of conventional thermal capacity that a variable generator can replace without compromising system reliability (Gross, et al., 2007).

- Capacity credits quantify the expectation of load demand exceeding generation capacity.

- The capacity credit is given as a percentage of the installed capacity of the renewable generators, for a percentage of penetration of the intermittent supplies in a system (say 20%) and is associated with costs of maintaining system reliability for the penetrations stated before (20%).

- Capacity credit is the measure of the amount of load that can be served on an electricity system by an intermittent source with no increase in the loss-of-load probability (LOLP).

- Capacity credit is the amount of power variable renewables can reliably be expected to produce at the times when demand for electricity is highest (OECD/IEAa, 2011).

- Capacity credit is a measure of a generating source’s contribution to system reliability and is tied to meeting peak demand/load.

- Capacity value is how much the resource is available at system peak to maintain system reliability.

- Capacity credit: probability of output during peak periods

Annex VII. Further results on the Quantitative Assessment of the Capacity Credit of RES

Date: May, June, July, August, September 2015
Authors: Julia Fernández Chozas (Julia F. Chozas, Consulting Engineer) and Brian Vad Mathiesen (Aalborg University, Sustainable Planning Group)

Goal:

I. Investigate the amount of production from RES in different consumption hours throughout a year

II. Compare the production and contribution from RES in two different systems, in an electricity-only system and in an energy system.

- Background of this report is the following definition of Capacity Credit: "*Capacity credit: amount of power variable renewable energies can reliably be expected to produce at the times when demand for electricity is highest*" (OECD/IEAa, 2011).

This study identifies different consumption patterns throughout a year and investigates the power production of different mixes of renewable energy sources in hours of low, average and peak electricity consumption.

Two systems are studied in the analysis:

- Electricity-only System.
- Integrated Energy System, which includes electricity, transport and heat sector.

- Selected periods in the study:
  - **Worst periods**: hours of maximum electricity consumption and minimum RES production.
  - **Peak-demand periods**: hours of maximum electricity consumption.
  - **Hi-RES periods**: hours of maximum RES production.
  - **Best periods**: hours of maximum RES production and minimum demand.

- Time spans selected are: 1-hour, 3-hour, 6-hour, 12-hour, 1-day, 3-day, 1-week, 1-month and 3-month. For all the time spans, the average values for the **consecutive** hours (as indicated) are considered

- Renewable energy sources (RES) included in the analyses are:
  - Offshore wind
  - Onshore wind
  - Wave, and
  - Solar PV

- Output parameters: the aggregated and individual Capacity Credit of the RES mix in the given electricity scenario.

Study periods:

- **Worst periods**: hours of maximum electricity consumption and minimum RES production.
- **Peak-demand periods**: hours of maximum electricity consumption.
- **Hi-RES periods**: hours of maximum RES production.
- **Best periods**: hours of maximum RES production and minimum demand.

Study time spans

- 1-hour values (8760 data points per year)

- 3-hour values (2920 data points per year)
- 6-hour values (1460 data points per year)
- 12-hour values (730 data points per year)
- 24-hour / 1-day values (365 data points per year)
- 3-hour values (122 data points per year)
- 7-day / 1-week values (52 data points per year)
- 1-month (12 data points per year)
- 3-month (4 data points per year)

For each time span, the average value of the indicated **consecutive** hour is calculated. For example, the 3-hour value is calculated as the average value of 3 consecutive hours.

Scenarios
Each of the scenarios below presents a different mix of RES production.
By investigating the power production in each scenario,

1. Year 2013 Scenario
2. CEESA2030 Scenario
3. CEESA2030-modified Scenario
4. Ambitious Offshore Wind Scenario
5. Ambitious Onshore Wind Scenario
6. Ambitious Wave Scenario
7. Ambitious Solar PV Scenario
8. Combined RES Scenario
9. ENS Wind 2035 Scenario
10. Offshore Wind - Only Scenario
11. Onshore Wind - Only Scenario
12. Wave - Only Scenario
13. Solar PV - Only Scenario
14. Heide et.al. (Århus) Scenario (Heide D., 2010)

Information on installed capacity and maximum production of each RES can be found in the Definition of Scenarios.

Methodology
The analysis investigates the power production of each RES for each of the 4 study periods, for each of the 9 time spans and for each of the 14 scenarios. The analysis is done over a year based on hourly values.

For example, the "Peak demand Scenario" investigates the production of offshore wind, onshore wind, wave and solar PV

- in the 1-hour interval of the year where electricity demand is highest
- in the 3-consecutive-hour interval of the year where electricity demand is highest
- in the 6-consecutive-hour interval of the year where electricity demand is highest
- etc.

The installed capacity of each RES and maximum production of each RES is defined according to the Scenario.

Modelling Background Data

- Deterministic study based on hourly year 2013 data from offshore wind, onshore wind and solar PV power production. Wave power production has been modelled based on 30-minute averaged wave measurements of H_{m0} and T_{02} at two different sites in the Danish North Sea, and on the expected power production of a commercial Wavestar unit.

- Classical Electricity Demand distribution data in <A) Electricity-only system approach> is:
    - For "Year 2013 Scenario", the electricity demand of year 2013.
    - For all other scenarios, the electricity demand of year 2035.

- Distribution data files in <B) Integrated energy system> are the same distribution files as in CEESA2030 analysis, except for the following ones:
    - Electricity demand, changed to electricity demand of year 2035.
    - Offshore wind, changed to distribution data for offshore wind in year 2013.
    - Onshore wind, changed to distribution data for onshore wind in year 2013.
    - Wave, changed to distribution data for wave power production in year 2013.
    - Solar PV, changed to distribution data for solar PV production in year 2013.

- <A) Electricity-only system approach> represents the classical electricity demand:
    - In year 2013, this is 33.5 TWh/y.
    - In CEESA2030, this is 21.85 TWh/y.

- <B) Integrated energy system approach> includes:
    - Classical electricity demand
    - Flexible demand, i.e. smart systems and smart appliances
    - Transport sector, i.e. electric vehicles
    - Heat pumps, i.e. big and industrial heat pumps
    - Electrolysers, including
        - CO_2 Hydrogenation (producing synthetic grid gas out of carbon recycling and hydrogen electrolysis)
        - Hydrogen
    - Households heat pumps and electric boilers
    - Total electricity demand in CEESA2030: 41.38 TWh.

- Adequacy analysis carried out by ENTSO-E are based on two reference points over a year, the third Wednesday of January at 7pm, and the third Wednesday of July, at 11am. In year 2013 and 2035, these date are:
    - In year 2013: 16th January from 6pm to 7pm, and 17th July from 10am to 11am
    - In year 2035: 17th January from 6pm to 7pm, and 18th July from 10am to 11am

- The 1-hour, 3-hour, 6-hour, etc. result might not be from the same day or hour. It represents the number of consecutive hour/hours in a year where the case of study occurs. **Future work**: study what happens in consecutive 1-hour, 3-hour, 6-hour, …, averaged values.

  Note: It might be unrealistic or biased the fact that in the scenarios of the analysis the expected annual RES production exceeds classical electricity demand (i.e. in CEESA2030 scenario RES production equals 27 TWh/y and the classical electricity demand is about 21 TWh/y). Nevertheless, this assumption has been drawn in accordance with national plans. Energistyrelsen's projections as in ENS Wind 2035 Scenario, RES production equals 32 TWh/y and classical electricity demand about 28 TWh/y. Having stated this, conclusions to be drawn in this report are based on these background data.

Approaches, nature of the studies:

A) Electricity-only system approach. This approach looks into the electricity sector isolated. It responds to the traditional perspective and covers only the classical electricity consumption.

B) Integrated energy systems approach. Here, the analysis is carried out from a holistic system perspective that integrates the consumption in all energy sectors: transport, heat, industry and electricity. Flexible electricity production and demand are also considered in this approach.

EnergyPLAN model simulations

A set of six diffrenet simulations (named hereafter Case Studies) are carried out with EnergyPLAN model. The three first simulations obey to a technical simulation and the last three to a market economic simulation. The differences among the three case studies analysed are in the interconnectors capacity able to use.

- Technical Simulation Strategy 3 (i.e. balancing both heat and electricity demands, reducing CHP also when partly needed for grid stabilisation).
    - VII. Case study I: no interconnectors capacity, i.e. export/import = 0 MW.
    - VIII. Case study II: interconnectors capacity as by end of year 2013, i.e. export/import = 5820 MW / 5080 MW.
    - IX. Case study III: interconnectors capacity as expected in year 2035, i.e. export/import = 10240 MW / 9780 MW.

- Market Economic Simulation:
    - X. Case study IV: no interconnectors capacity, i.e. export/import = 0 MW.
    - XI. Case study V: interconnectors capacity as by end of year 2013, i.e. export/import = 5820 MW / 5080 MW.
    - XII. Case study VI: interconnectors capacity as expected in year 2035, i.e. export/import = 10240 MW / 9780 MW.

Capacity factors

The capacity factors of each of the technologies of the study have been evaluated in the report. Accordingly, capacity factors considered in the calculations are conservative and representative of the sectors. The average capacity factors for the RES of the study are the following. (These numbers are based on year 2013 averages on Denmark; as estated before for wave energy this is an estimate):

	Offshore wind	**Onshore wind**	**Wave Prod.**	**PV Prod.**
Capacity Factor (%)	40%	25%	32%	11%

Overall, the capacity factors influence the resulting CC of the different RES in the worst-case and in the stress scenarios. Thus, CC is sensitive to the Cf. Nevertheless, the estimates of Cf included in this study are based on representative averages that can be considered good enough.

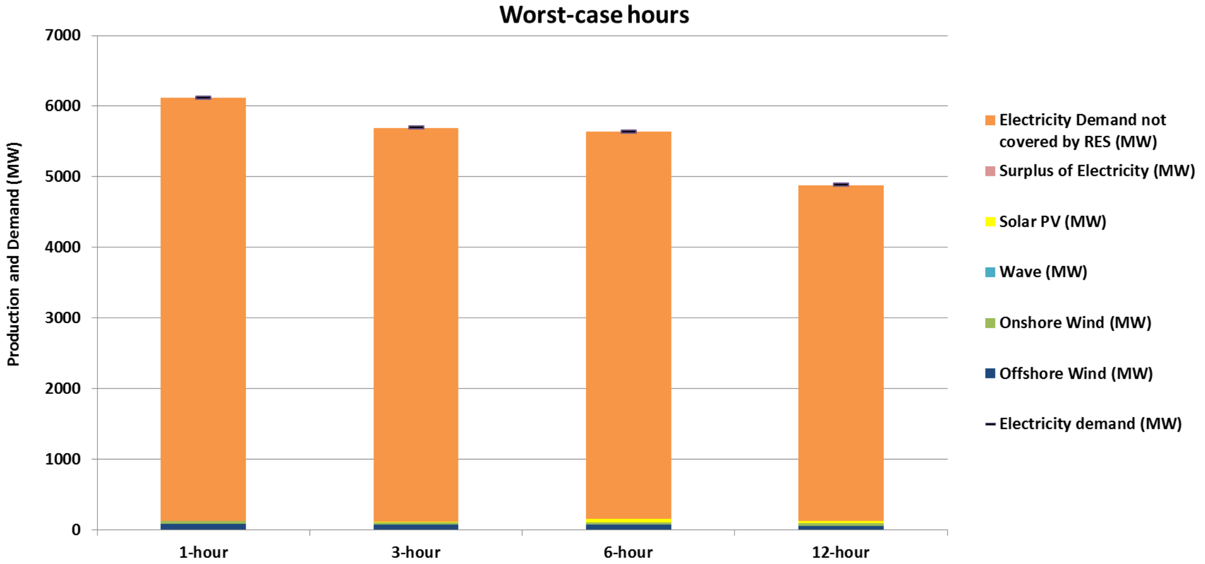
1) Modelling Tool: In-house developed Model

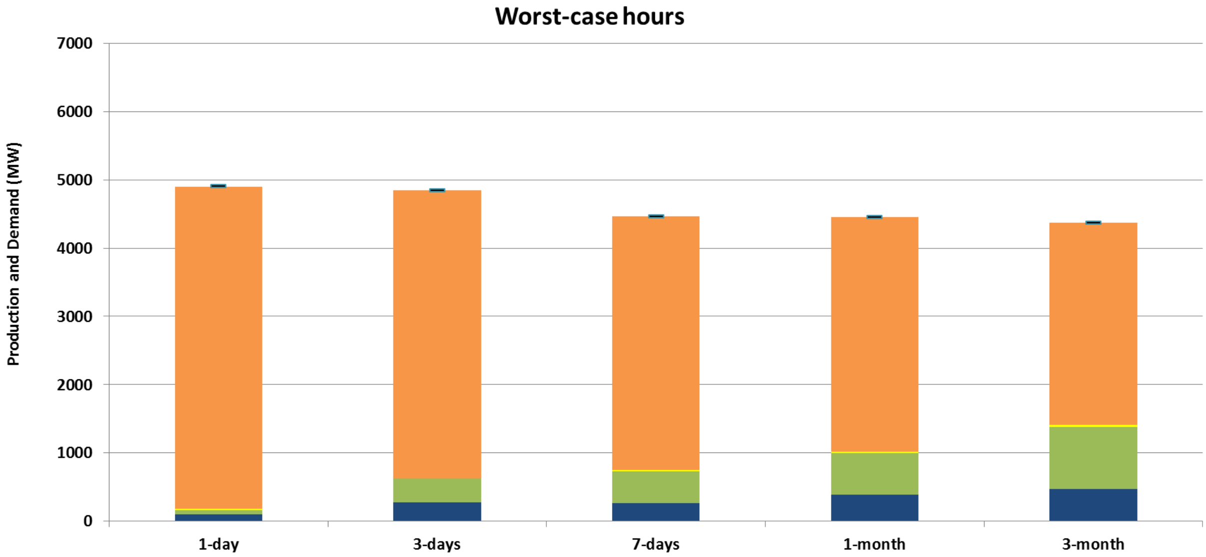
1.1) ELECTRICITY-ONLY SYSTEM APPROACH

1.1.1) Worst periods: hours of maximum El. Demand and minimum RES production

This case study identifies the time periods where the difference between electricity consumption and RES production is highest.

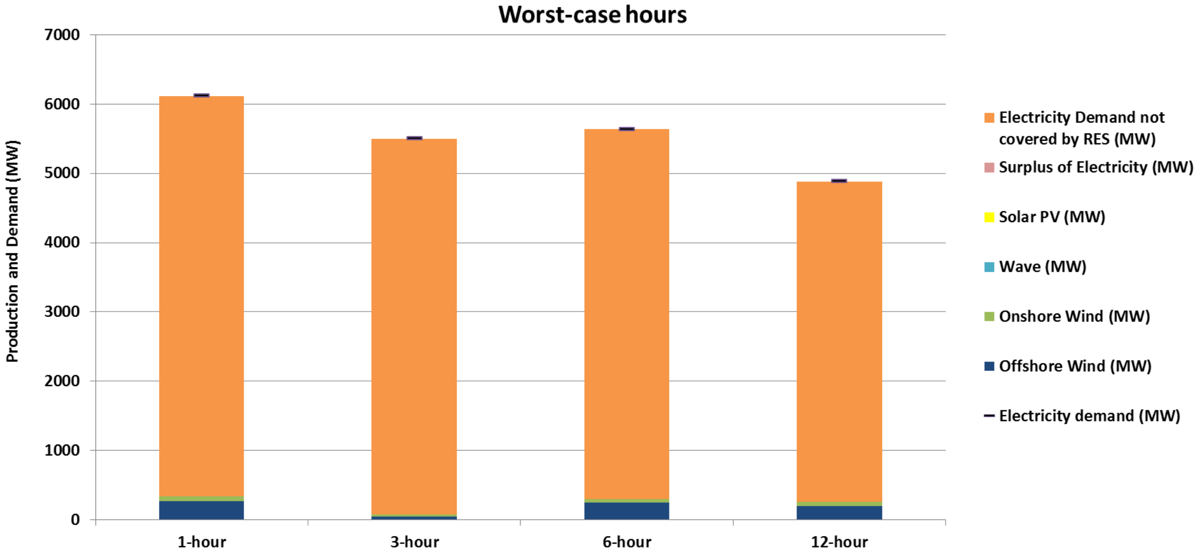
Year 2013

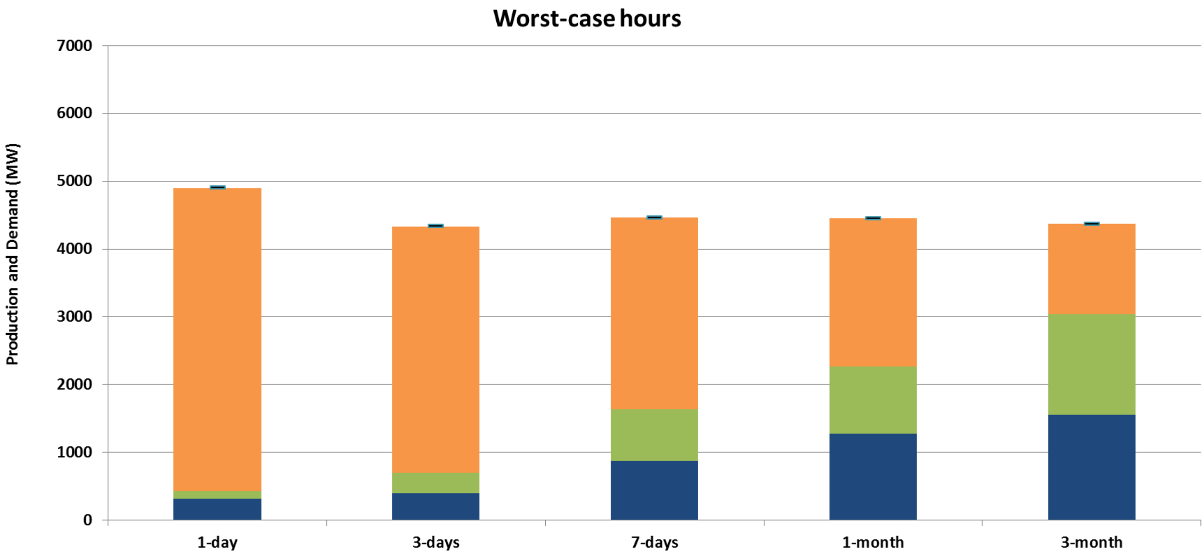




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	24-jan, 17:00	2%	6%	1%	0%	0%
3-hour	24-jan, 15:00	2%	6%	1%	0%	3%
6-hour	24-jan, 12:00	3%	6%	1%	0%	11%
12-hour	24-jan, 12:00	2%	5%	1%	0%	5%
24-hour / 1-day	24-jan, 00:00	3%	8%	2%	0%	4%
72-hour / 3-day	16-jan, 00:00	12%	22%	10%	0%	1%
168-hour / 1-week	12-feb, 00:00	14%	21%	13%	0%	3%
1-month	February	19%	30%	17%	0%	4%
3-month (year quarter)	Jan-Feb-March	27%	37%	26%	0%	6%

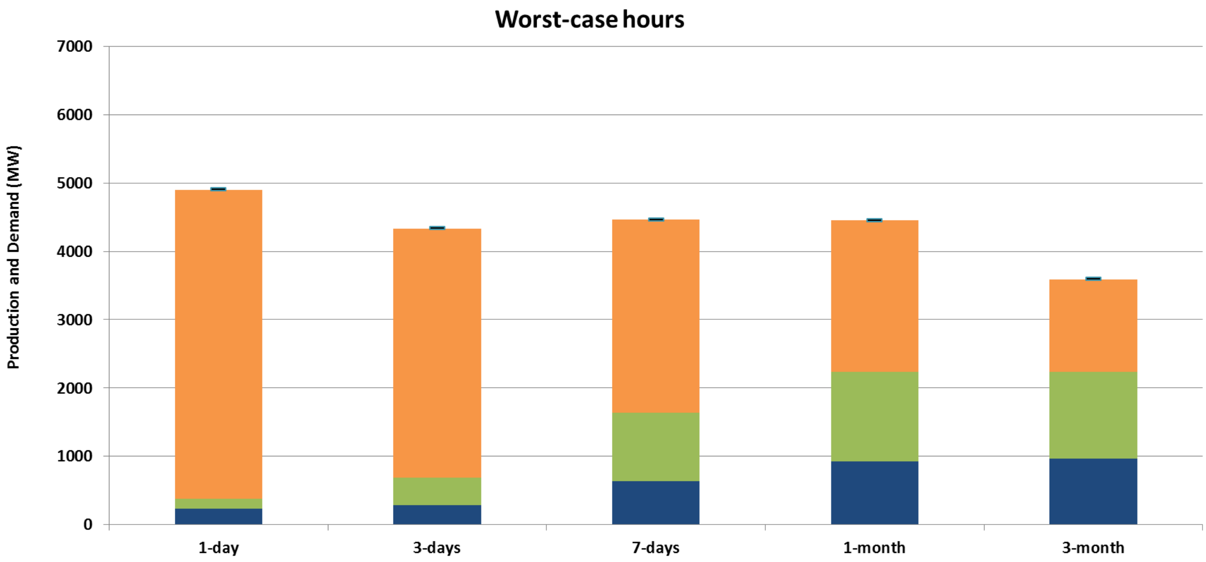
Ambitious Offshore Wind Scenario





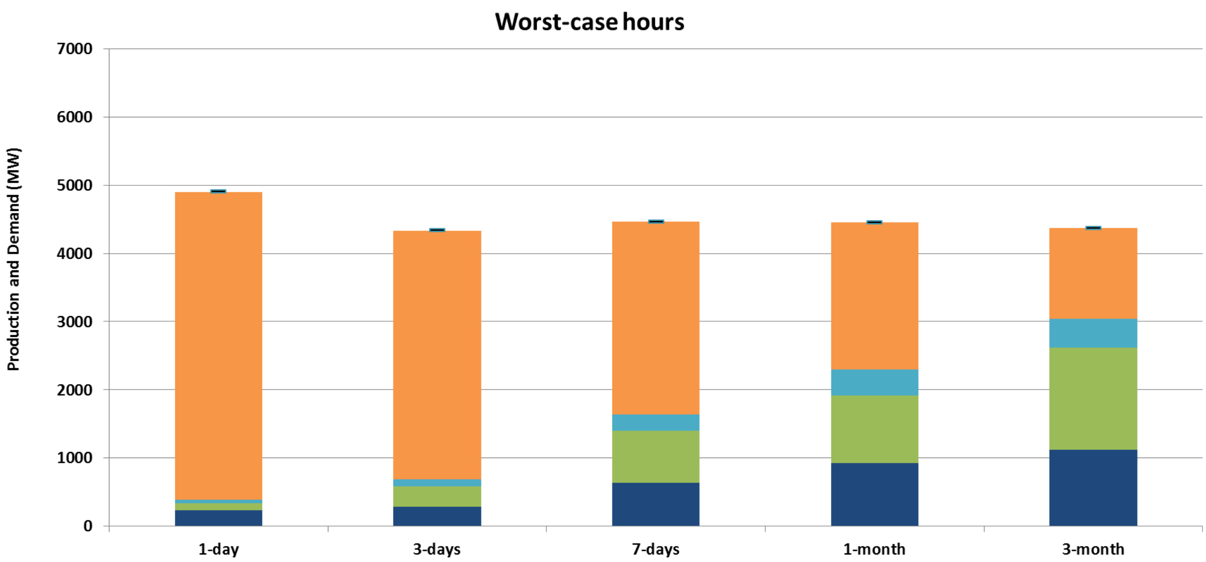
Capacity Credits (in % of Installed Capacity)						
Time-frames	**Date & Hour**	**All RES Combined**	**Offshore wind**	**Onshore wind**	**Wave**	**PV Prod.**
1-hour	24-jan, 17:00	3%	6%	1%	0%	0%
3-hour	13-feb, 09:00	1%	1%	1%	0%	0%
6-hour	24-jan, 12:00	3%	6%	1%	0%	0%
12-hour	24-jan, 12:00	3%	5%	1%	0%	0%
24-hour / 1-day	24-jan, 00:00	4%	8%	2%	0%	0%
72-hour / 3-day	15-feb, 00:00	7%	9%	5%	0%	0%
168-hour / 1-week	12-feb, 00:00	16%	21%	13%	0%	0%
1-month	February	23%	30%	17%	0%	0%
3-month (year quarter)	Jan-Feb-March	31%	37%	26%	0%	0%

Ambitious Onshore Wind Scenario



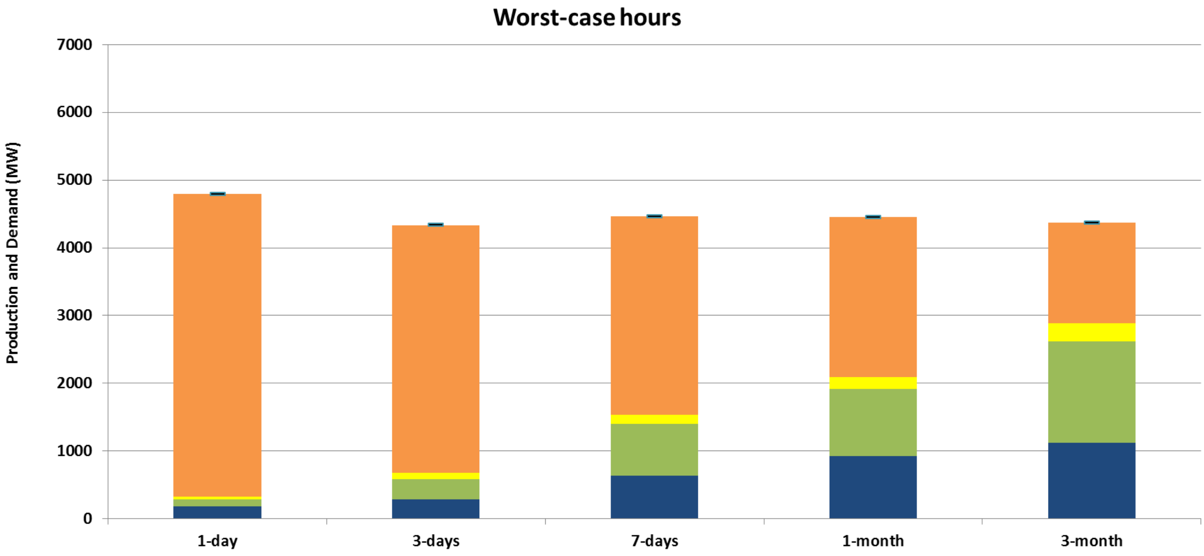
Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	24-jan, 17:00	3%	6%	1%	0%	0%
3-hour	24-jan, 15:00	2%	6%	1%	0%	0%
6-hour	24-jan, 12:00	2%	6%	1%	0%	0%
12-hour	24-jan, 12:00	2%	5%	1%	0%	0%
24-hour / 1-day	24-jan, 00:00	3%	8%	2%	0%	0%
72-hour / 3-day	15-feb, 00:00	6%	9%	5%	0%	0%
168-hour / 1-week	12-feb, 00:00	15%	21%	13%	0%	0%
1-month	February	21%	30%	17%	0%	0%
3-month (year quarter)	July-Aug-Sept	21%	32%	17%	0%	0%

Ambitious Wave Scenario



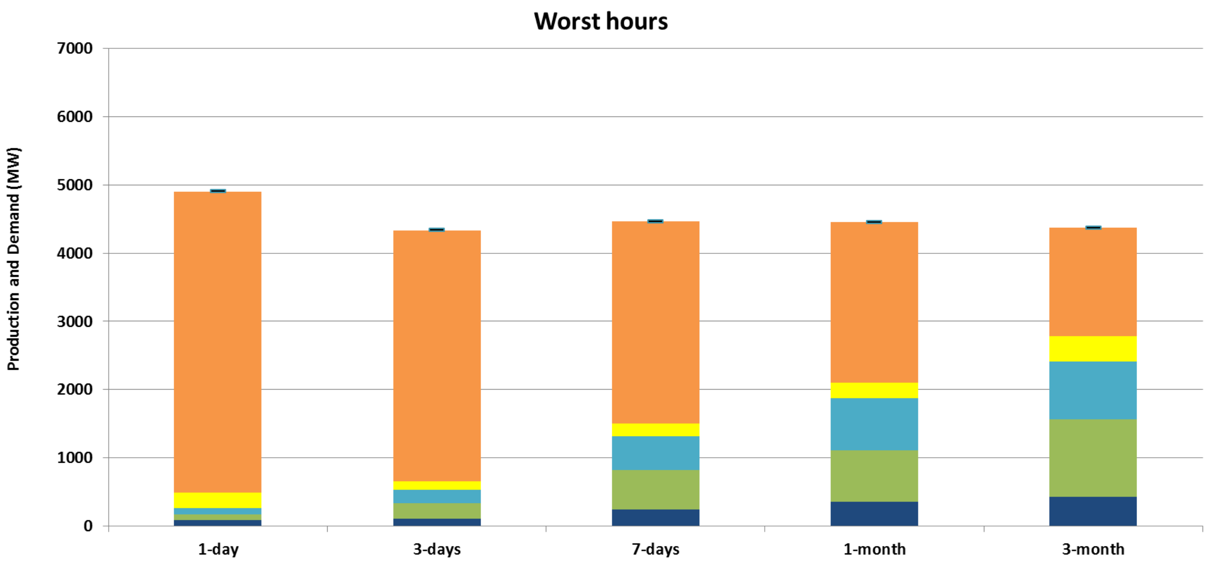
Capacity Credits (in % of Installed Capacity)						
Time-frames	**Date & Hour**	**All RES Combined**	**Offshore wind**	**Onshore wind**	**Wave**	**PV Prod.**
1-hour	24-jan, 17:00	3%	6%	1%	3%	0%
3-hour	24-jan, 15:00	3%	6%	1%	3%	0%
6-hour	24-jan, 12:00	3%	6%	1%	3%	0%
12-hour	24-jan, 12:00	2%	5%	1%	3%	0%
24-hour / 1-day	24-jan, 00:00	4%	8%	2%	3%	0%
72-hour / 3-day	15-feb, 00:00	7%	9%	5%	7%	0%
168-hour / 1-week	12-feb, 00:00	16%	21%	13%	17%	0%
1-month	February	22%	30%	17%	26%	0%
3-month (year quarter)	Jan-Feb-March	30%	37%	26%	29%	0%

Ambitious Solar PV Scenario



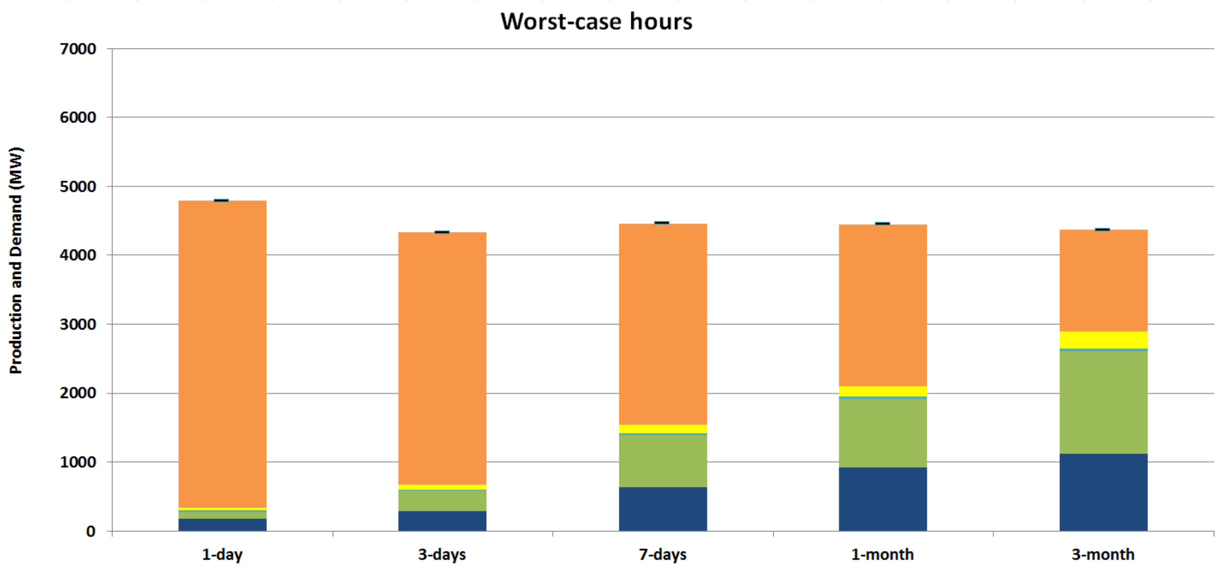
Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	24-jan, 17:00	2%	6%	1%	0%	0%
3-hour	24-jan, 15:00	3%	6%	1%	0%	3%
6-hour	16-jan, 12:00	2%	3%	2%	0%	3%
12-hour	24-jan, 12:00	3%	5%	1%	0%	5%
24-hour / 1-day	16-jan, 00:00	2%	6%	2%	0%	1%
72-hour / 3-day	15-feb, 00:00	5%	9%	5%	0%	2%
168-hour / 1-week	12-feb, 00:00	12%	21%	13%	0%	3%
1-month	February	16%	30%	17%	0%	4%
3-month (year quarter)	Jan-Feb-March	22%	37%	26%	0%	6%

Combined RES Scenario



Capacity Credits (in % of Installed Capacity)						
Time-frames	**Date & Hour**	**All RES Combined**	**Offshore wind**	**Onshore wind**	**Wave**	**PV Prod.**
1-hour	24-jan, 17:00	2%	6%	1%	3%	0%
3-hour	24-jan, 15:00	3%	6%	1%	3%	3%
6-hour	25-jan, 06:00	4%	10%	4%	4%	4%
12-hour	24-jan, 12:00	3%	5%	1%	3%	5%
24-hour / 1-day	24-jan, 00:00	3%	8%	2%	3%	4%
72-hour / 3-day	15-feb, 00:00	5%	9%	5%	7%	2%
168-hour / 1-week	12-feb, 00:00	11%	21%	13%	17%	3%
1-month	February	15%	30%	17%	26%	4%
3-month (year quarter)	Jan-Feb-March	20%	37%	26%	29%	6%

CEESA 2030 modified Scenario

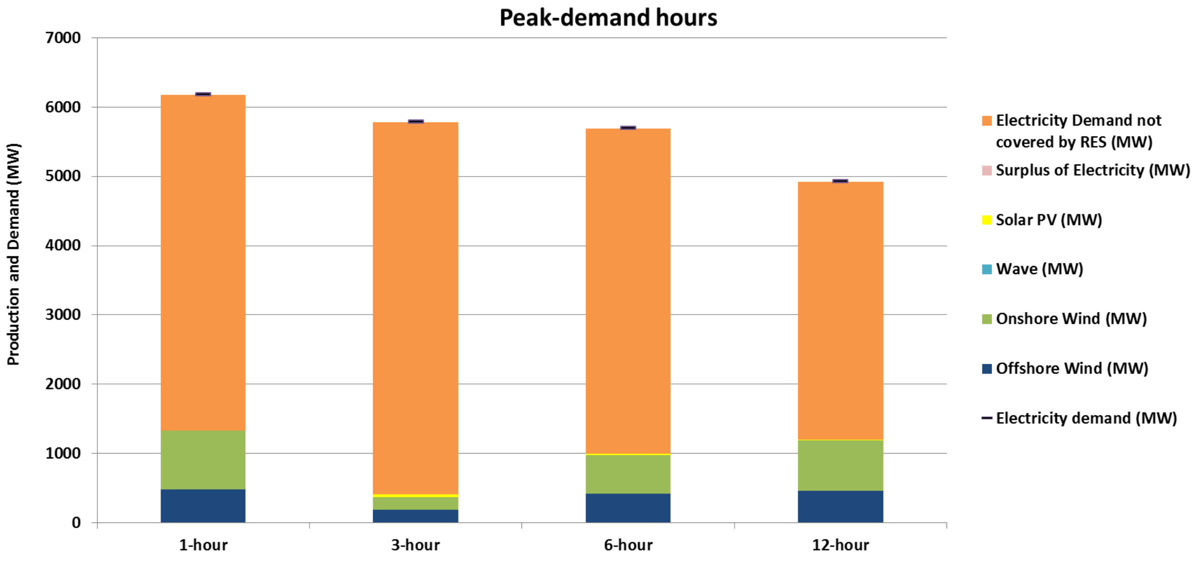


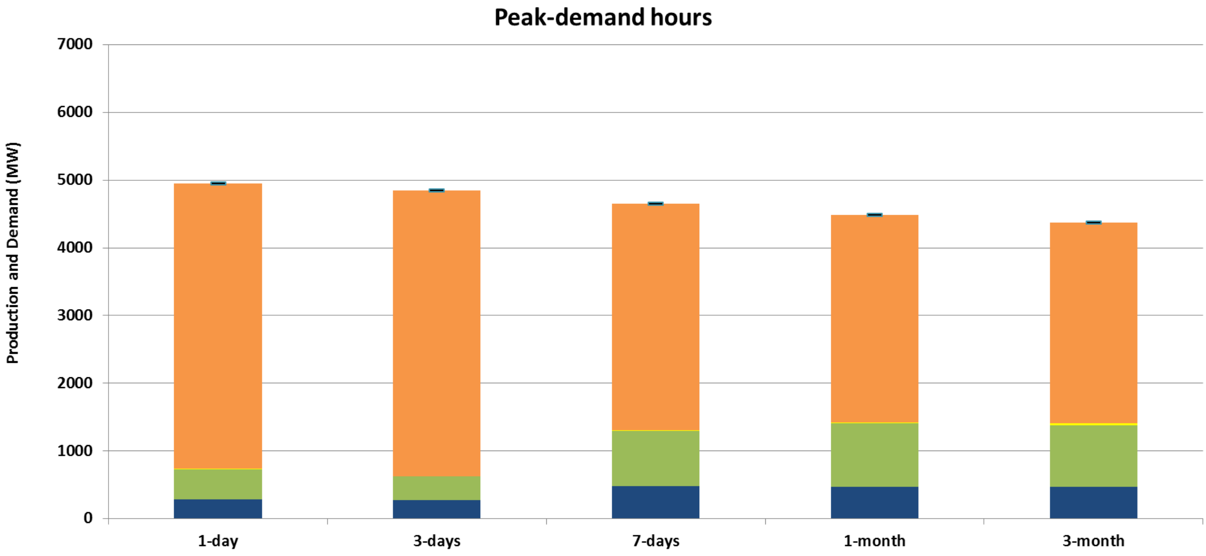
Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	24-jan, 17:00	2%	6%	1%	3%	0%
3-hour	24-jan, 15:00	3%	6%	1%	3%	3%
6-hour	16-jan, 12:00	3%	3%	2%	15%	3%
12-hour	24-jan, 12:00	3%	5%	1%	3%	5%
24-hour / 1-day	16-jan, 00:00	3%	6%	2%	16%	1%
72-hour / 3-day	15-feb, 00:00	5%	9%	5%	7%	2%
168-hour / 1-week	12-feb, 00:00	12%	21%	13%	17%	3%
1-month	February	16%	30%	17%	26%	4%
3-month (year quarter)	Jan-Feb-March	23%	37%	26%	29%	6%

1.1.2) Peak demand periods: hours of highest electricity demand

This case study identifies the time periods where the electricity consumption is highest.

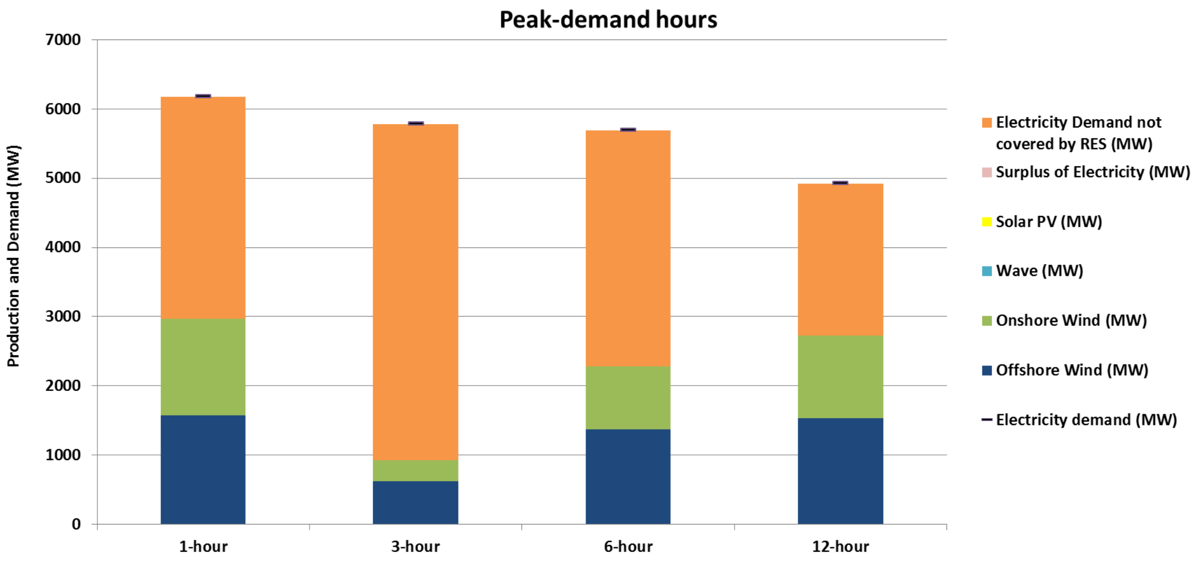
Year 2013

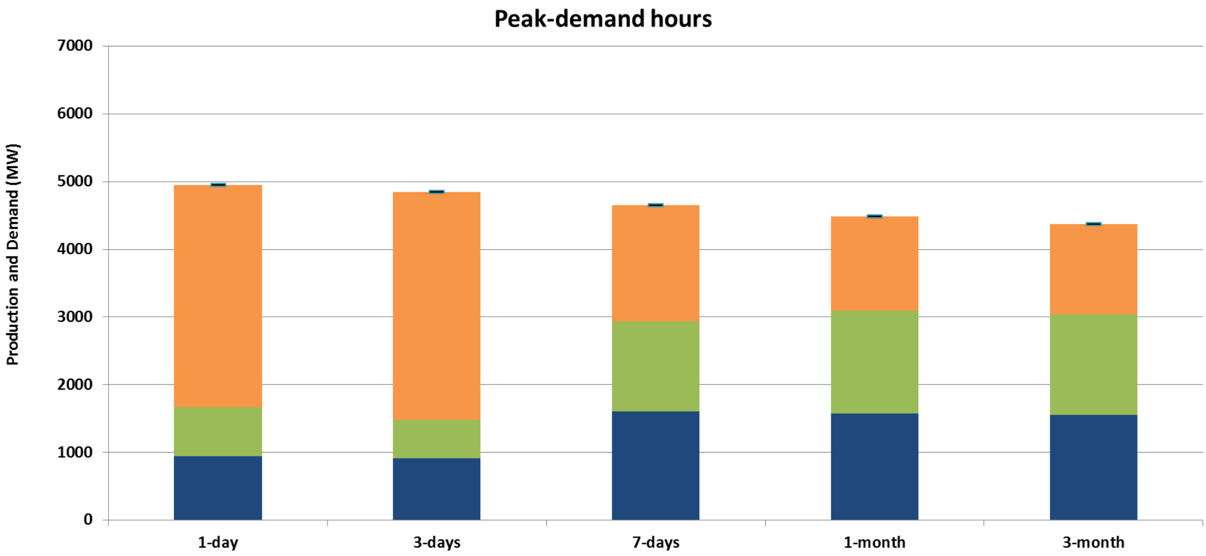




Capacity Credits (in % of Installed Capacity)						
Time-frames	**Date & Hour**	**All RES Combined**	**Offshore wind**	**Onshore wind**	**Wave**	**PV Prod.**
1-hour	25-jan, 17:00	25%	37%	24%	0%	0%
3-hour	25-jan, 09:00	8%	15%	5%	0%	7%
6-hour	25-jan, 12:00	19%	33%	16%	0%	5%
12-hour	25-jan, 12:00	23%	36%	21%	0%	2%
24-hour / 1-day	25-jan, 00:00	14%	23%	12%	0%	2%
72-hour / 3-day	16-jan, 00:00	12%	22%	10%	0%	1%
168-hour / 1-week	22-jan, 00:00	25%	38%	23%	0%	2%
1-month	January	27%	37%	26%	0%	2%
3-month (year quarter)	Jan-Feb-March	27%	37%	26%	0%	6%

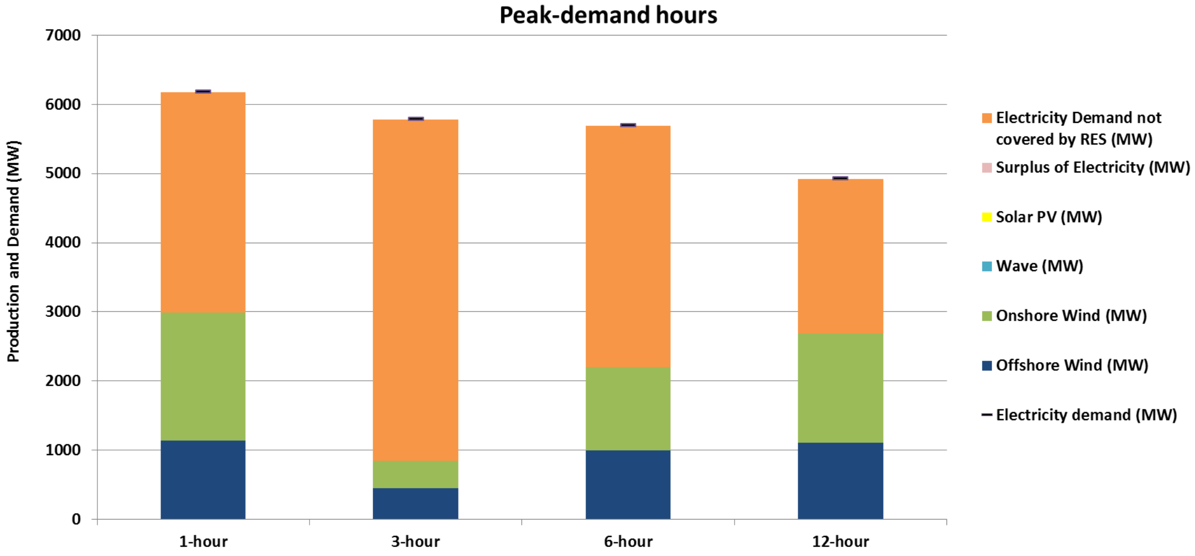
Ambitious Offshore Wind Scenario

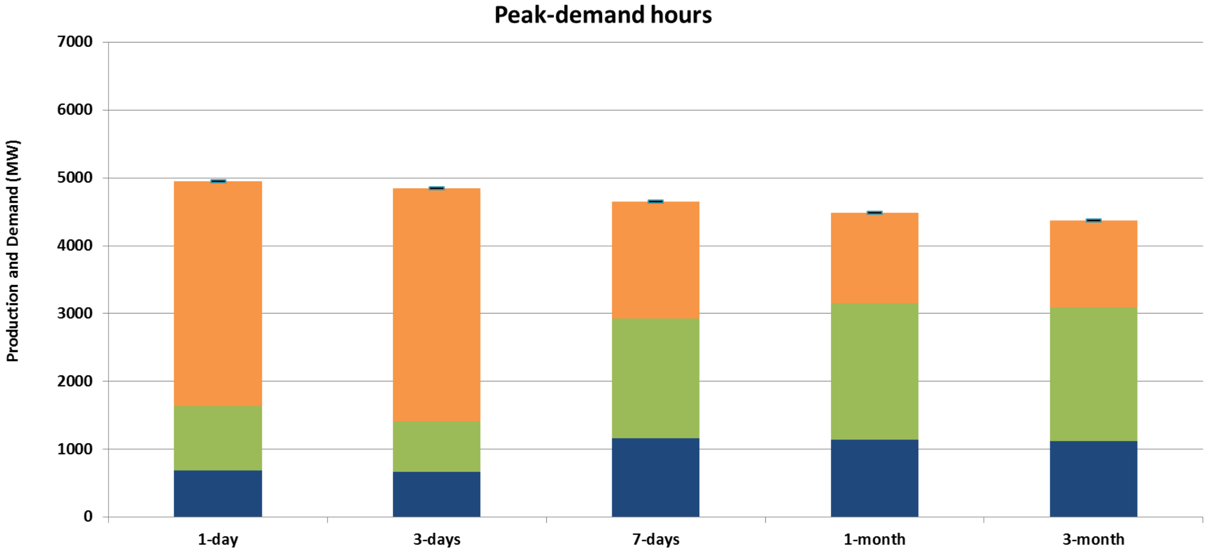




Capacity Credits (in % of Installed Capacity)						
Time-frames	**Date & Hour**	**All RES Combined**	**Offshore wind**	**Onshore wind**	**Wave**	**PV Prod.**
1-hour	25-jan, 17:00	30%	37%	24%	0%	0%
3-hour	25-jan, 09:00	9%	15%	5%	0%	0%
6-hour	25-jan, 12:00	23%	33%	16%	0%	0%
12-hour	25-jan, 12:00	27%	36%	21%	0%	0%
24-hour / 1-day	25-jan, 00:00	17%	23%	12%	0%	0%
72-hour / 3-day	16-jan, 00:00	15%	22%	10%	0%	0%
168-hour / 1-week	22-jan, 00:00	29%	38%	23%	0%	0%
1-month	January	31%	37%	26%	0%	0%
3-month (year quarter)	Jan-Feb-March	31%	37%	26%	0%	0%

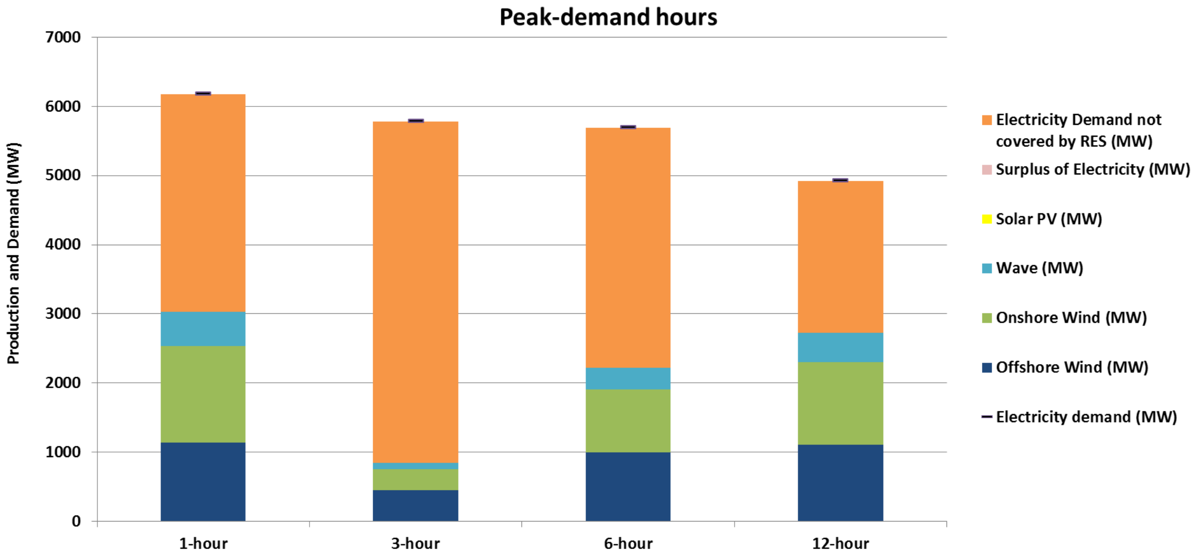
Ambitious Onshore Wind Scenario

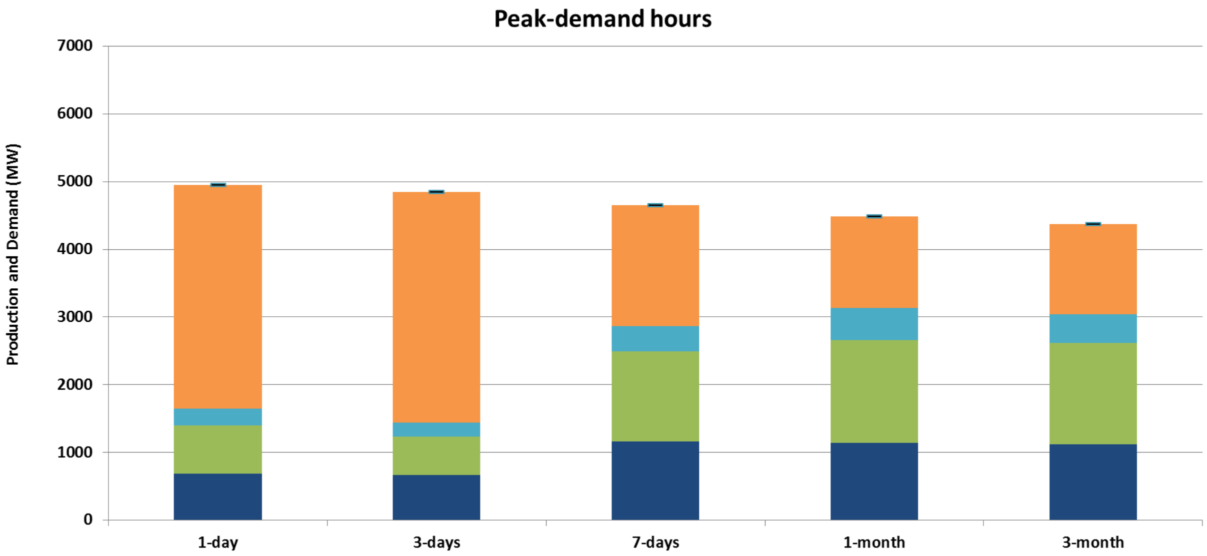




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	25-jan, 17:00	28%	37%	24%	0%	0%
3-hour	25-jan, 09:00	8%	15%	5%	0%	0%
6-hour	25-jan, 12:00	21%	33%	16%	0%	0%
12-hour	25-jan, 12:00	25%	36%	21%	0%	0%
24-hour / 1-day	25-jan, 00:00	15%	23%	12%	0%	0%
72-hour / 3-day	16-jan, 00:00	13%	22%	10%	0%	0%
168-hour / 1-week	22-jan, 00:00	27%	38%	23%	0%	0%
1-month	January	30%	37%	26%	0%	0%
3-month (year quarter)	Jan-Feb-March	29%	37%	26%	0%	0%

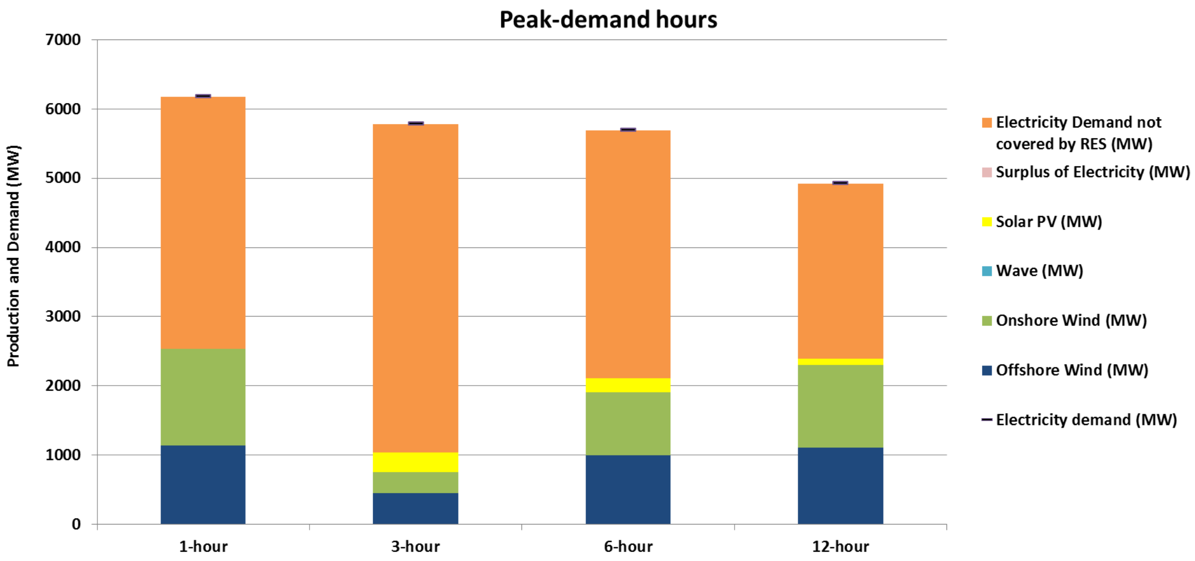
Ambitious Wave Scenario

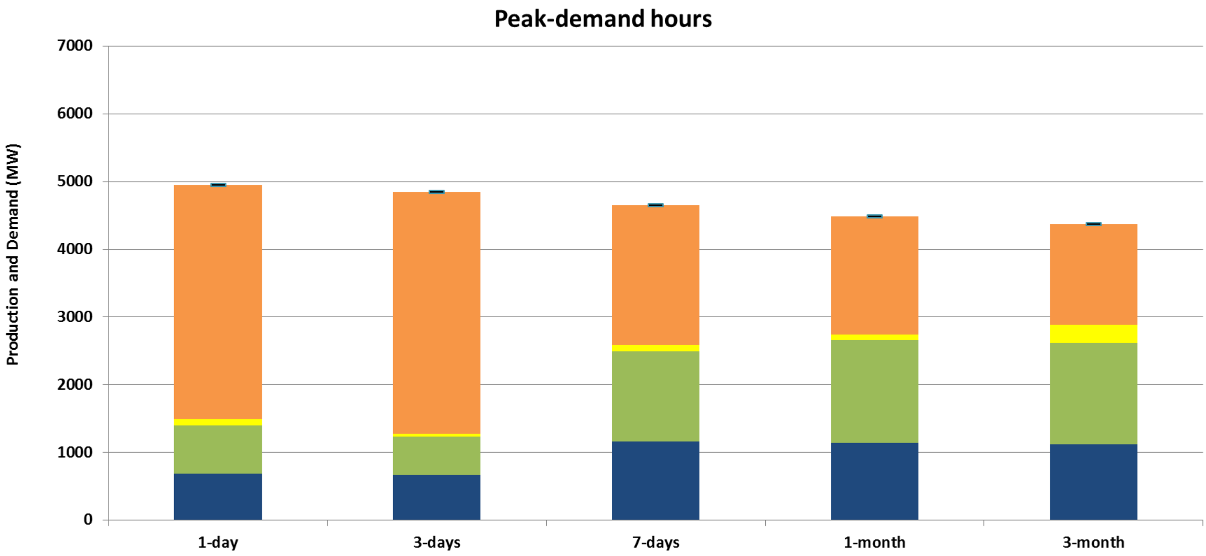




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	25-jan, 17:00	30%	37%	24%	34%	0%
3-hour	25-jan, 09:00	8%	15%	5%	6%	0%
6-hour	25-jan, 12:00	22%	33%	16%	22%	0%
12-hour	25-jan, 12:00	27%	36%	21%	29%	0%
24-hour / 1-day	25-jan, 00:00	16%	23%	12%	17%	0%
72-hour / 3-day	16-jan, 00:00	14%	22%	10%	14%	0%
168-hour / 1-week	22-jan, 00:00	28%	38%	23%	26%	0%
1-month	January	31%	37%	26%	32%	0%
3-month (year quarter)	Jan-Feb-March	30%	37%	26%	29%	0%

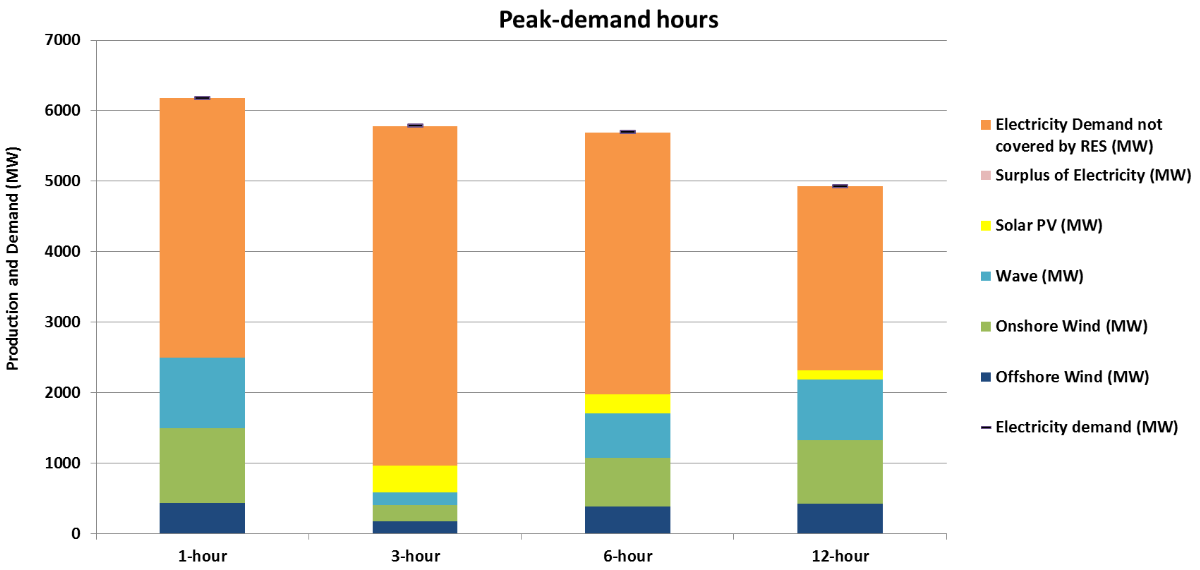
Ambitious Solar PV Scenario

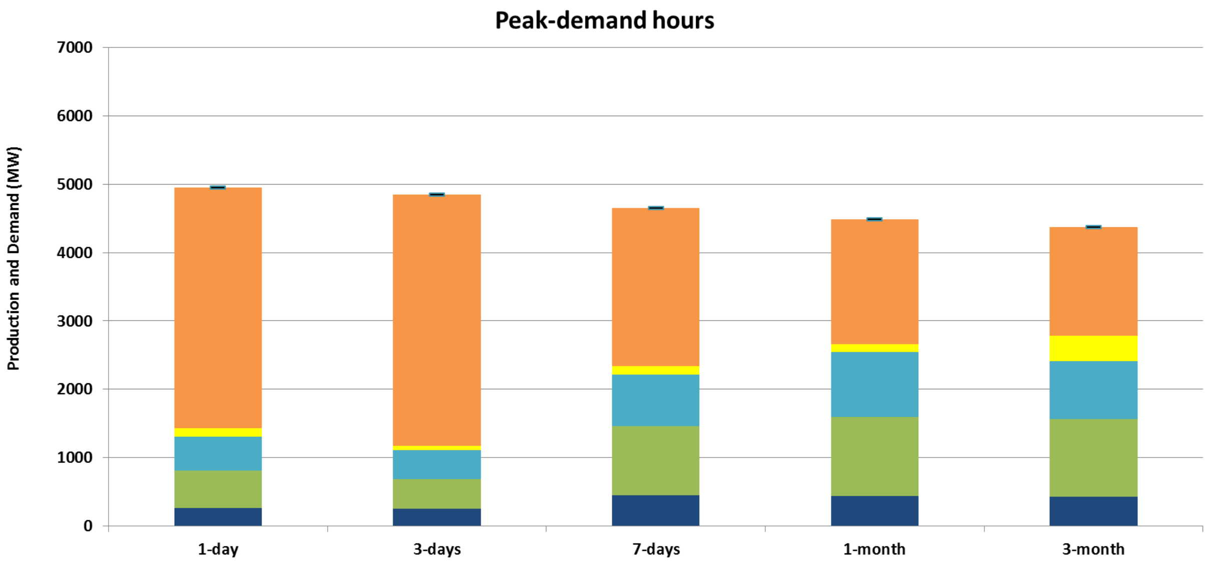




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	25-jan, 17:00	19%	37%	24%	0%	0%
3-hour	25-jan, 09:00	8%	15%	5%	0%	7%
6-hour	25-jan, 12:00	16%	33%	16%	0%	5%
12-hour	25-jan, 12:00	18%	36%	21%	0%	2%
24-hour / 1-day	25-jan, 00:00	11%	23%	12%	0%	2%
72-hour / 3-day	16-jan, 00:00	10%	22%	10%	0%	1%
168-hour / 1-week	22-jan, 00:00	20%	38%	23%	0%	2%
1-month	January	21%	37%	26%	0%	2%
3-month (year quarter)	Jan-Feb-March	22%	37%	26%	0%	6%

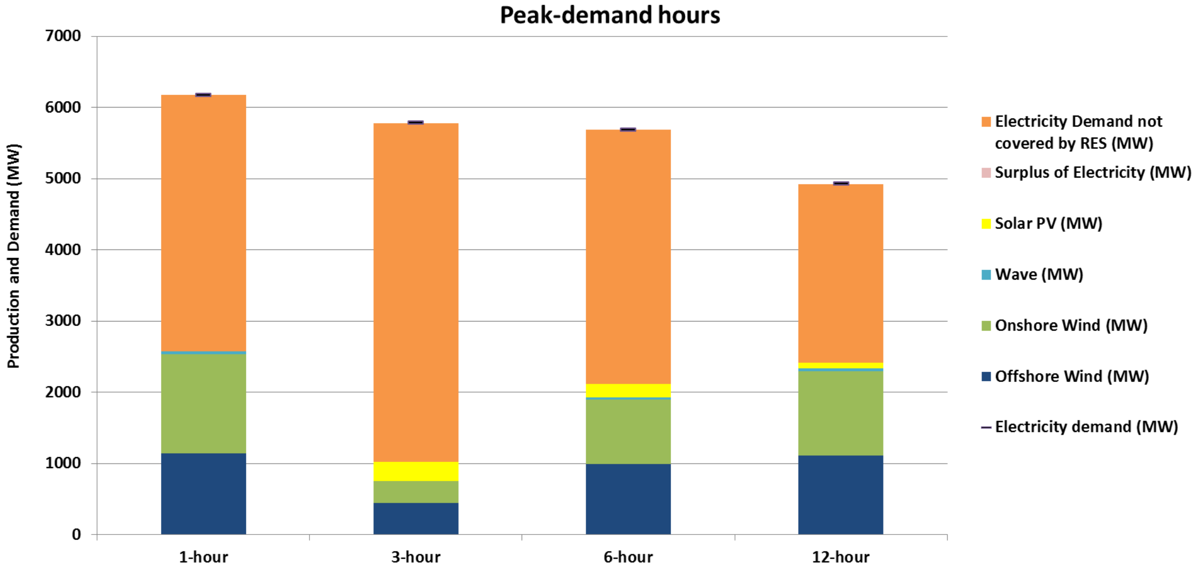
Combined RES Scenario

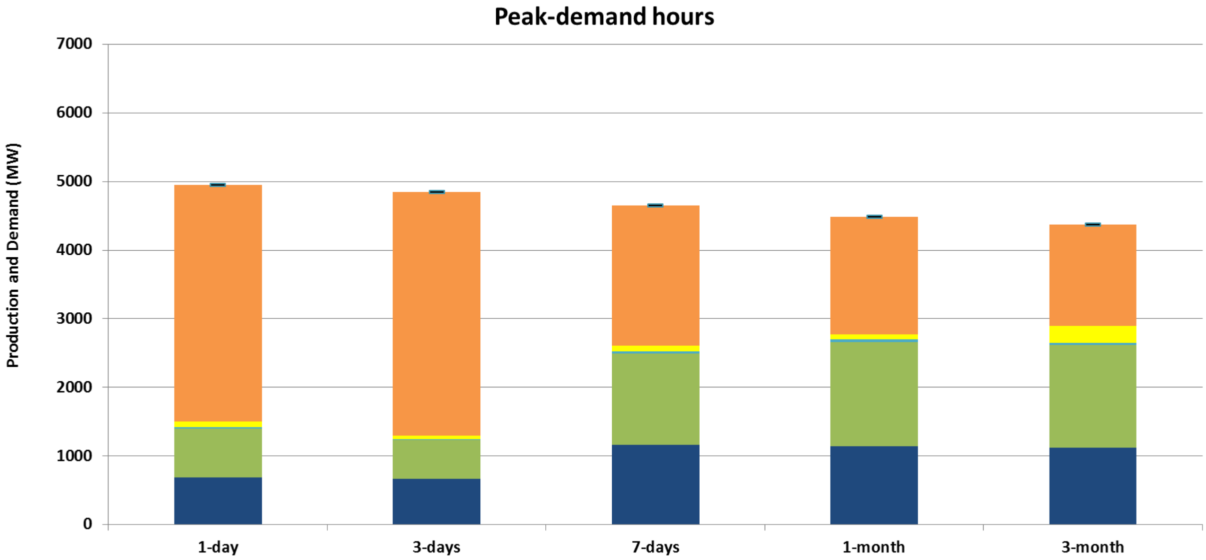




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	25-jan, 17:00	18%	37%	24%	34%	0%
3-hour	25-jan, 09:00	7%	15%	5%	6%	7%
6-hour	25-jan, 12:00	14%	33%	16%	22%	5%
12-hour	25-jan, 12:00	16%	36%	21%	29%	2%
24-hour / 1-day	25-jan, 00:00	10%	23%	12%	17%	2%
72-hour / 3-day	16-jan, 00:00	8%	22%	10%	14%	1%
168-hour / 1-week	22-jan, 00:00	17%	38%	23%	26%	2%
1-month	January	19%	37%	26%	32%	2%
3-month (year quarter)	Jan-Feb-March	20%	37%	26%	29%	6%

CEESA 2030 modified Scenario





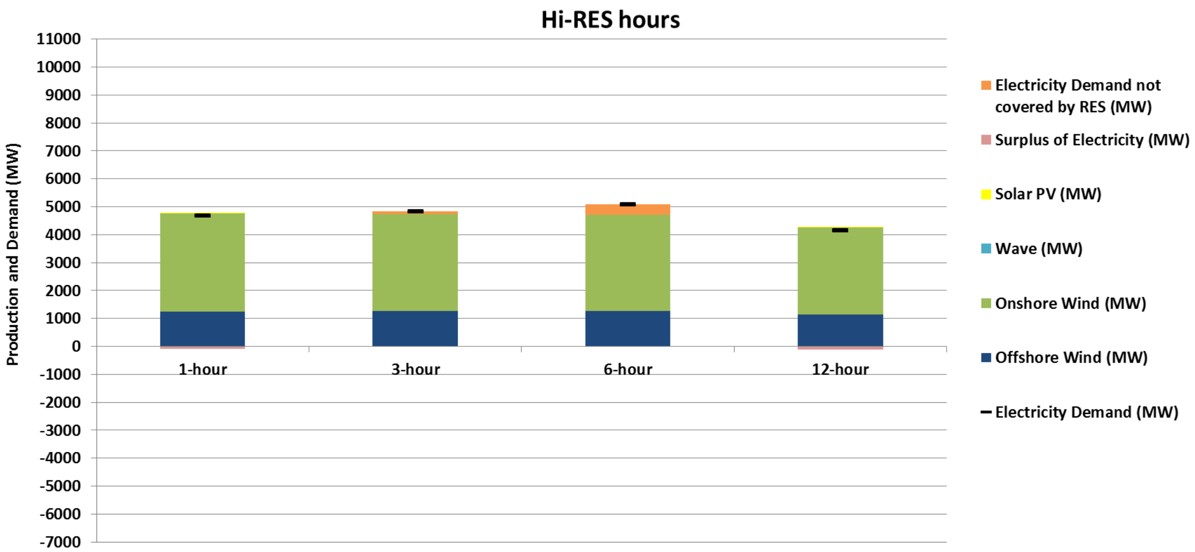
Capacity Credits (in % of Installed Capacity)						
Time-frames	**Date & Hour**	**All RES Combined**	**Offshore wind**	**Onshore wind**	**Wave**	**PV Prod.**
1-hour	25-jan, 17:00	20%	37%	24%	34%	0%
3-hour	25-jan, 09:00	8%	15%	5%	6%	7%
6-hour	25-jan, 12:00	16%	33%	16%	22%	5%
12-hour	25-jan, 12:00	19%	36%	21%	29%	2%
24-hour / 1-day	25-jan, 00:00	12%	23%	12%	17%	2%
72-hour / 3-day	16-jan, 00:00	10%	22%	10%	14%	1%
168-hour / 1-week	22-jan, 00:00	20%	38%	23%	26%	2%
1-month	January	22%	37%	26%	32%	2%
3-month (year quarter)	Jan-Feb-March	23%	37%	26%	29%	6%

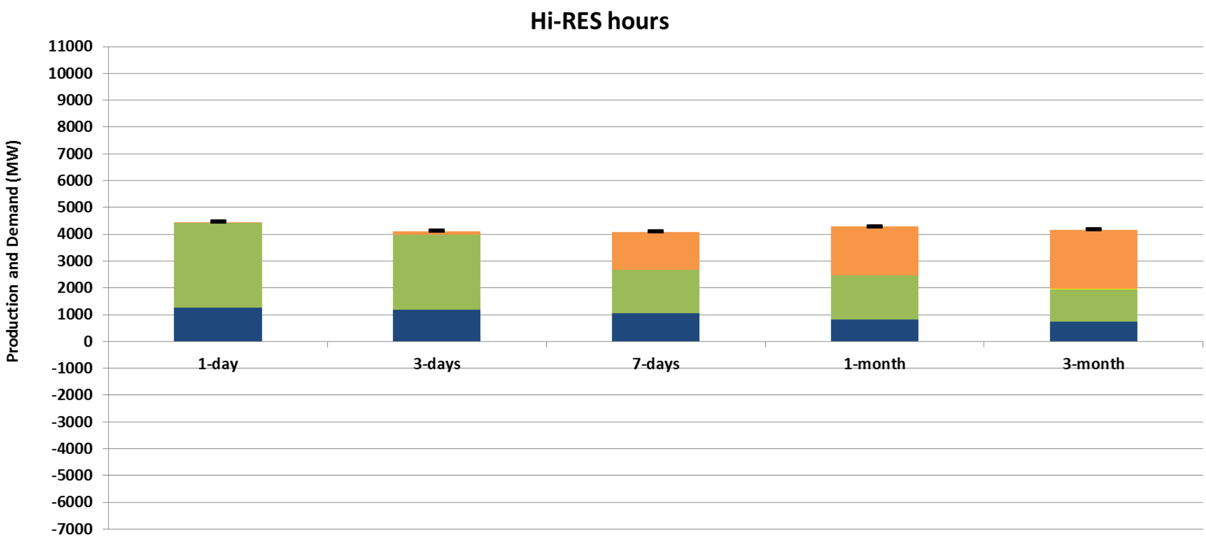
1.1.3) Hi-RES periods: hours of maximum RES production

This case study identifies the time periods where the combined RES production is highest.

In some scenarios (i.e. Year 2013, ENS Wind 2035) Solar PV production is close to zero or equal to zero for every time span of the analysis, due to the fact that the Hi-RES hour(s) are those in the evening or in December month.

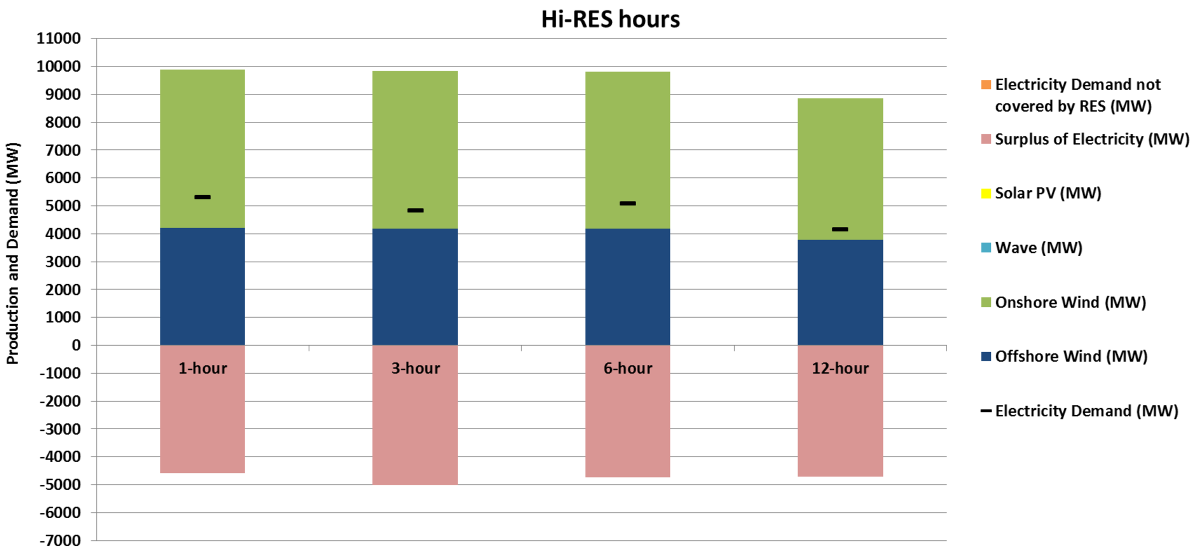
Year 2013

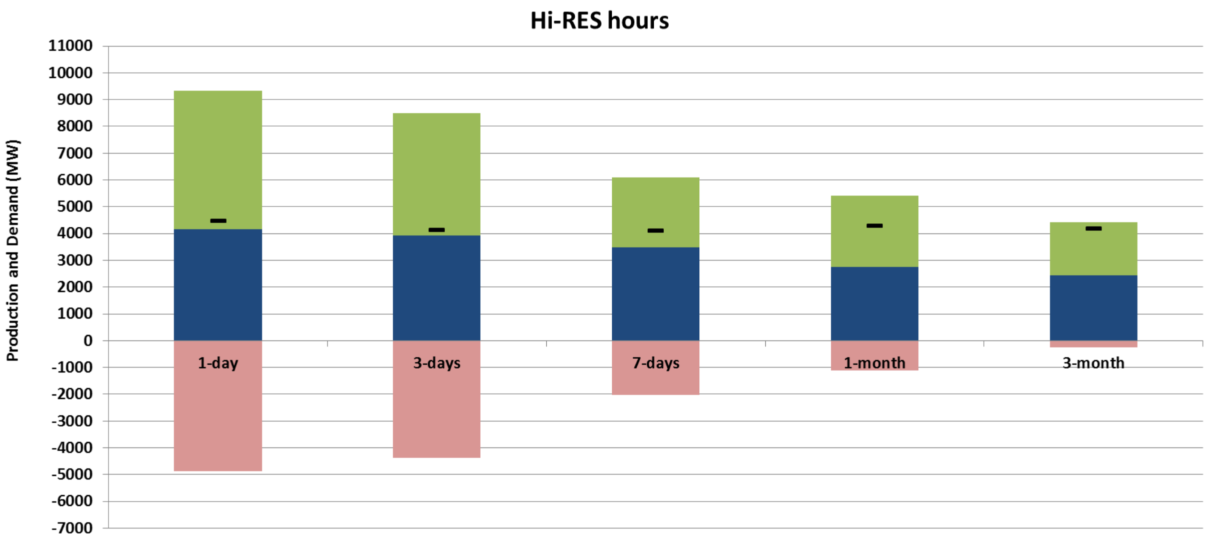




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-06-02 13:00	90%	98%	99%	0%	1%
3-hour	2035-06-02 12:00	90%	99%	98%	0%	0%
6-hour	2035-06-02 12:00	89%	100%	98%	0%	0%
12-hour	2035-06-02 12:00	81%	90%	88%	0%	0%
24-hour / 1-day	2035-06-02 00:00	84%	99%	90%	0%	0%
72-hour / 3-day	2035-12-21 00:00	76%	94%	79%	0%	1%
168-hour / 1-week	2035-10-22 00:00	51%	82%	46%	0%	5%
1-month	December	47%	65%	46%	0%	1%
3-month (year quarter)	Oct-Nov-Dec	37%	58%	34%	0%	3%

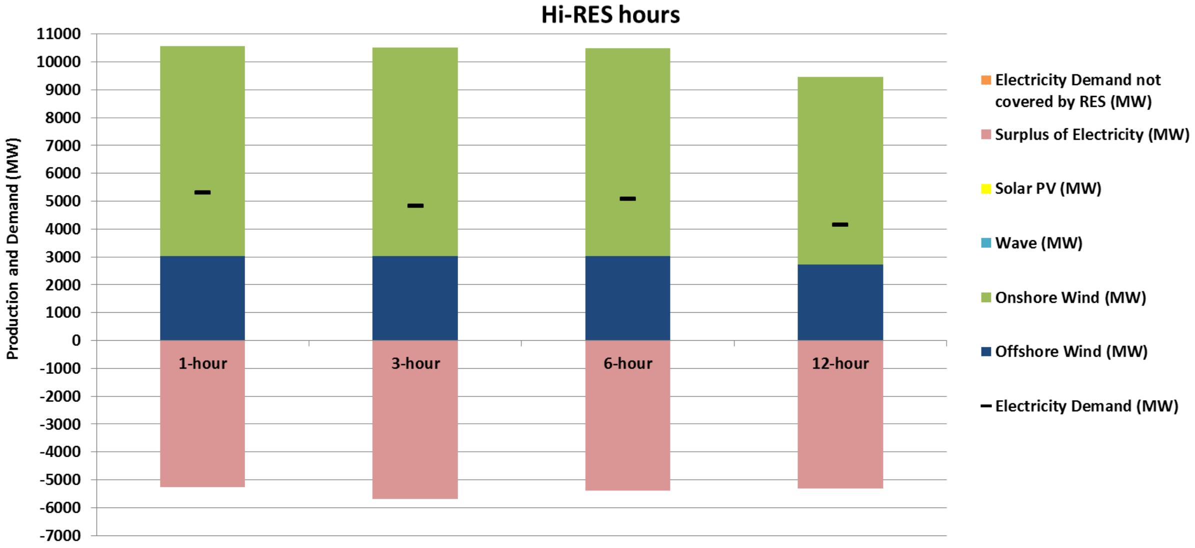
Ambitious Offshore Wind Scenario

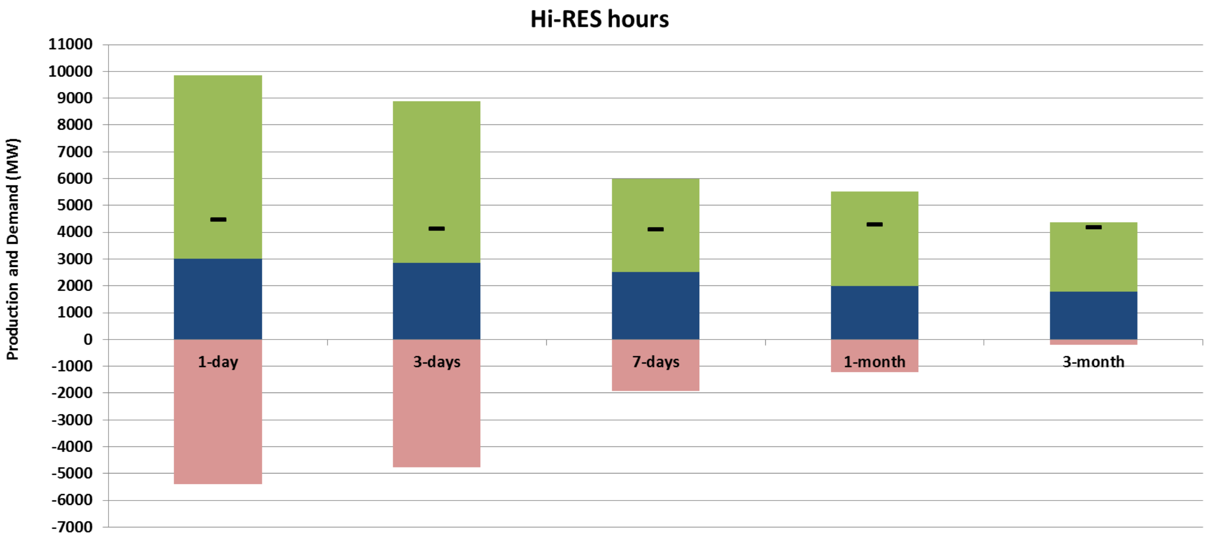




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-06-02 13:00	99%	100%	99%	0%	0%
3-hour	2035-06-02 12:00	99%	99%	98%	0%	0%
6-hour	2035-06-02 12:00	98%	100%	98%	0%	0%
12-hour	2035-06-02 12:00	89%	90%	88%	0%	0%
24-hour / 1-day	2035-06-02 00:00	93%	99%	90%	0%	0%
72-hour / 3-day	2035-12-21 00:00	85%	94%	79%	0%	0%
168-hour / 1-week	2035-10-22 00:00	61%	82%	46%	0%	0%
1-month	December	54%	65%	46%	0%	0%
3-month (year quarter)	Oct-Nov-Dec	44%	58%	34%	0%	0%

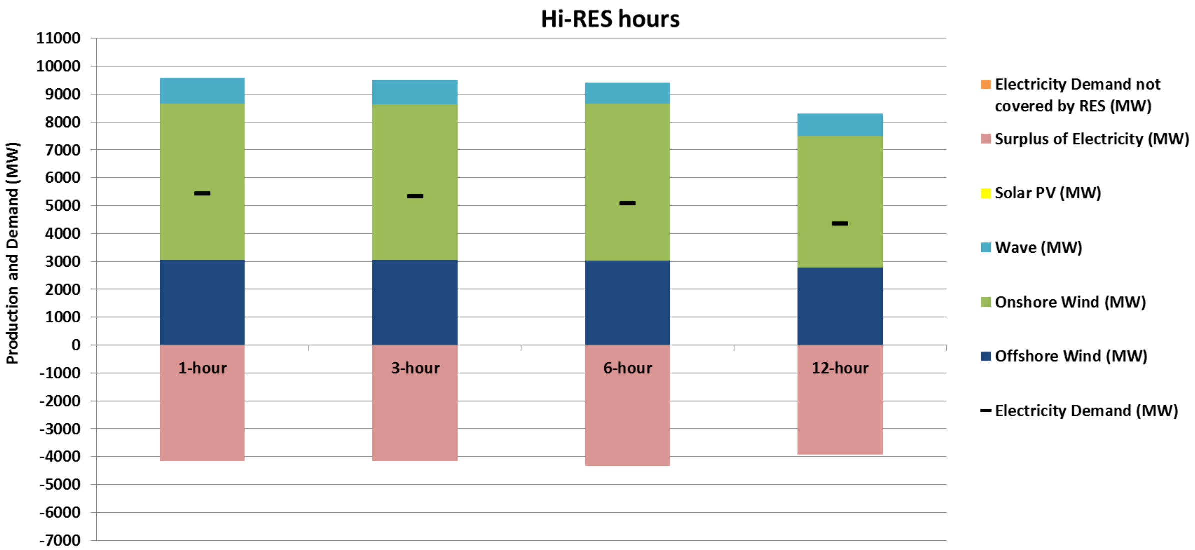
Ambitious Onshore Wind Scenario

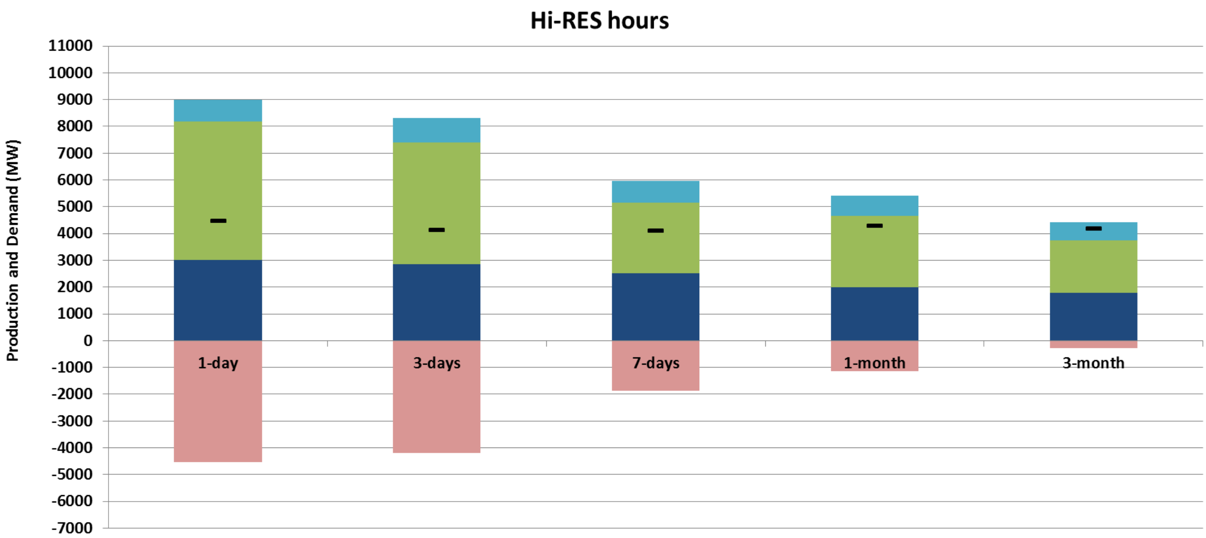




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-06-02 13:00	99%	100%	99%	0%	0%
3-hour	2035-06-02 12:00	98%	99%	98%	0%	0%
6-hour	2035-06-02 12:00	98%	100%	98%	0%	0%
12-hour	2035-06-02 12:00	89%	90%	88%	0%	0%
24-hour / 1-day	2035-06-02 00:00	92%	99%	90%	0%	0%
72-hour / 3-day	2035-12-21 00:00	83%	94%	79%	0%	0%
168-hour / 1-week	2035-10-22 00:00	56%	82%	46%	0%	0%
1-month	December	52%	65%	46%	0%	0%
3-month (year quarter)	Oct-Nov-Dec	41%	58%	34%	0%	0%

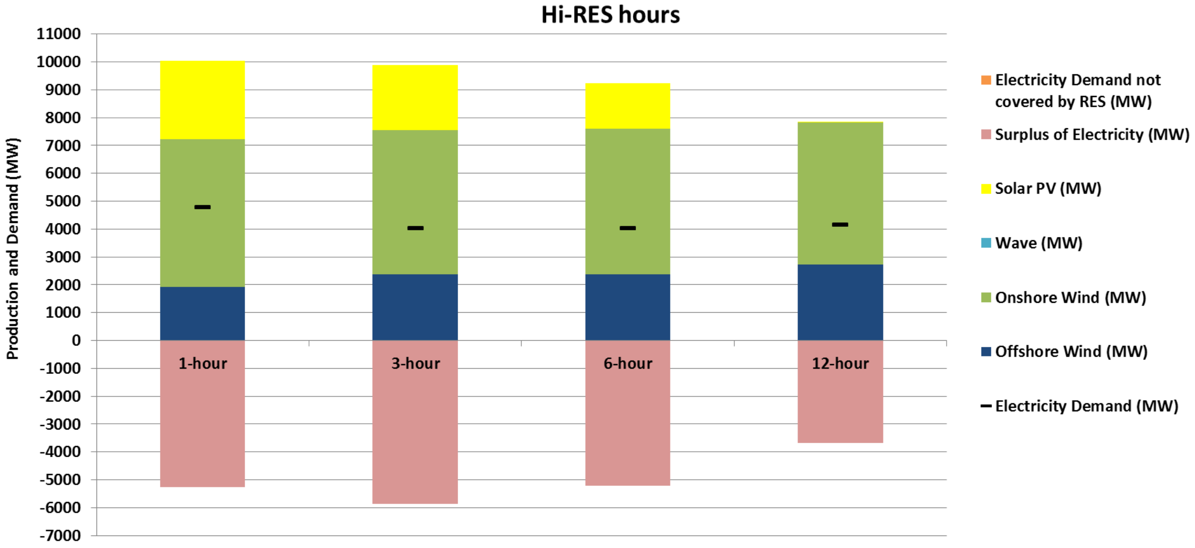
Ambitious Wave Scenario

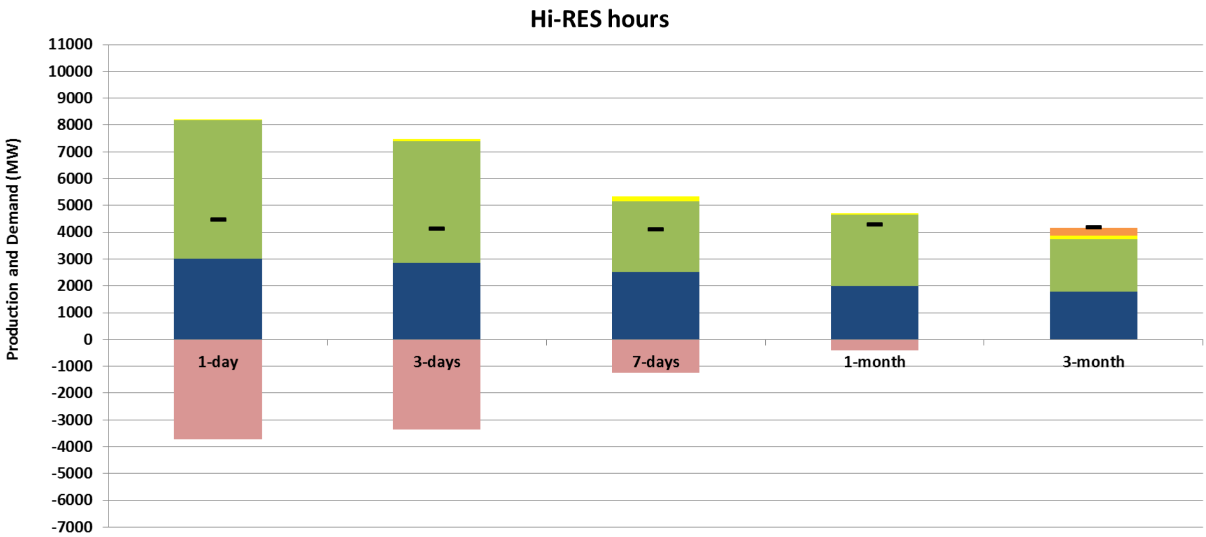




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-06-02 13:00	93%	100%	97%	65%	0%
3-hour	2035-06-02 12:00	93%	100%	97%	59%	0%
6-hour	2035-06-02 12:00	92%	100%	98%	51%	0%
12-hour	2035-06-02 12:00	81%	92%	82%	55%	0%
24-hour / 1-day	2035-06-02 00:00	87%	99%	90%	55%	0%
72-hour / 3-day	2035-12-21 00:00	81%	94%	79%	62%	0%
168-hour / 1-week	2035-10-22 00:00	58%	82%	46%	56%	0%
1-month	December	53%	65%	46%	53%	0%
3-month (year quarter)	Oct-Nov-Dec	43%	58%	34%	48%	0%

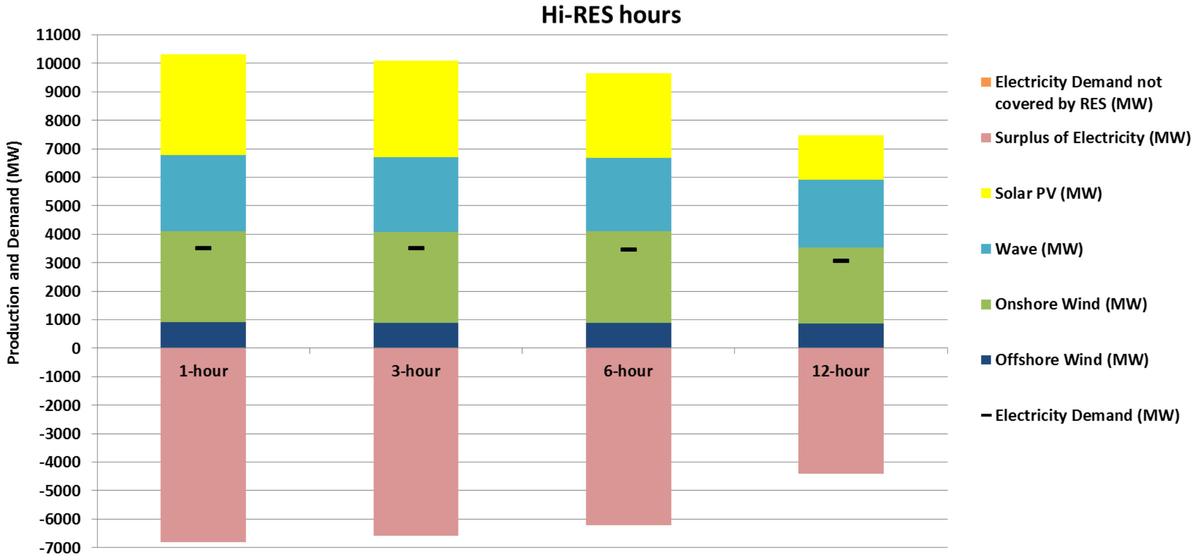
Ambitious Solar PV Scenario

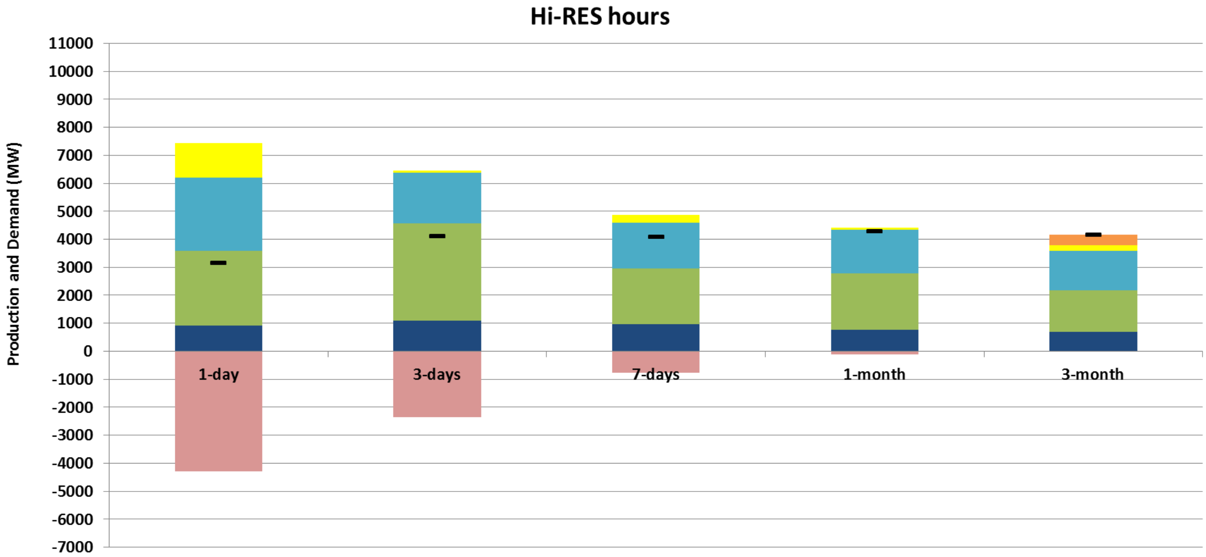




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-06-02 13:00	77%	63%	92%	0%	67%
3-hour	2035-06-02 12:00	76%	78%	90%	0%	55%
6-hour	2035-06-02 12:00	71%	78%	90%	0%	39%
12-hour	2035-06-02 12:00	60%	90%	88%	0%	0%
24-hour / 1-day	2035-06-02 00:00	63%	99%	90%	0%	0%
72-hour / 3-day	2035-12-21 00:00	57%	94%	79%	0%	1%
168-hour / 1-week	2035-10-22 00:00	41%	82%	46%	0%	5%
1-month	December	36%	65%	46%	0%	1%
3-month (year quarter)	Oct-Nov-Dec	30%	58%	34%	0%	3%

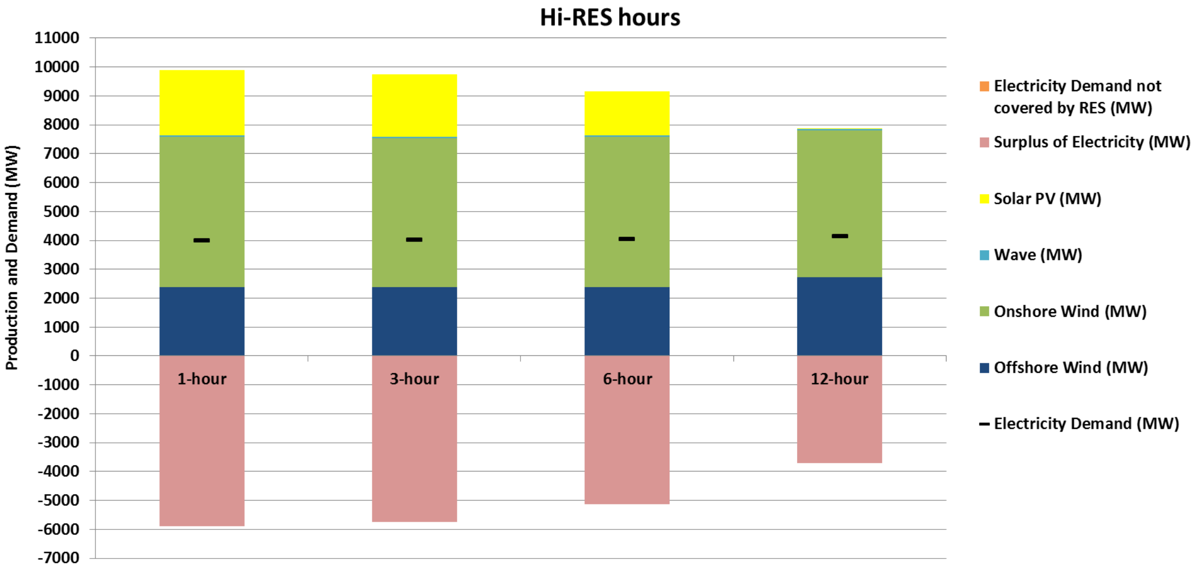
Combined RES Scenario

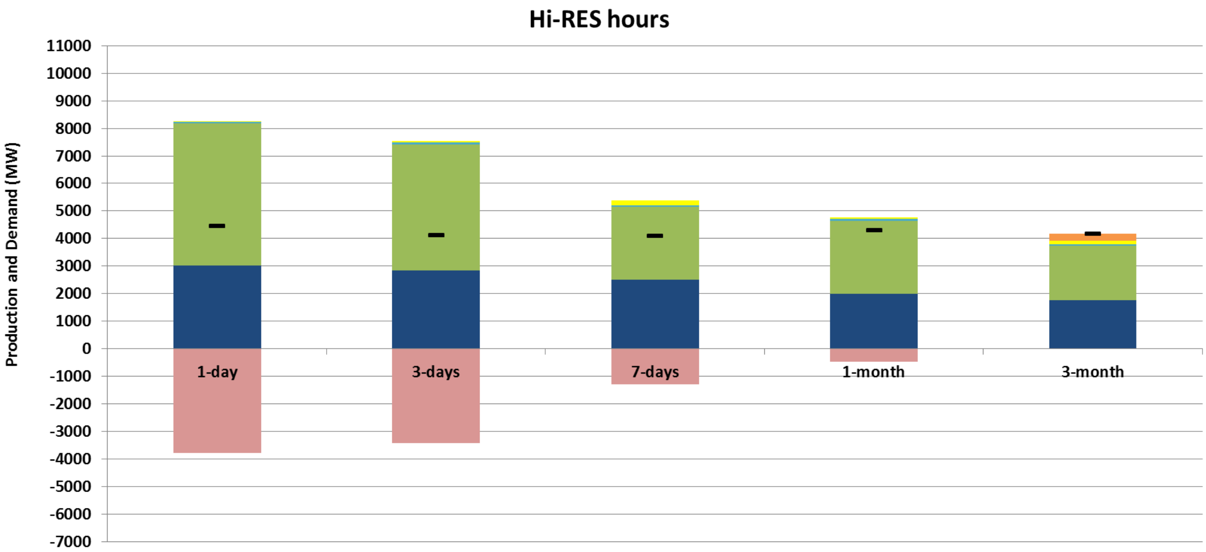




Capacity Credits (in % of Installed Capacity)						
Time-frames	**Date & Hour**	**All RES Combined**	**Offshore wind**	**Onshore wind**	**Wave**	**PV Prod.**
1-hour	2035-06-02 13:00	73%	78%	73%	91%	62%
3-hour	2035-06-02 12:00	71%	76%	73%	90%	60%
6-hour	2035-06-02 12:00	68%	77%	74%	88%	52%
12-hour	2035-06-02 12:00	53%	73%	61%	81%	28%
24-hour / 1-day	2035-06-02 00:00	53%	78%	61%	90%	22%
72-hour / 3-day	2035-12-21 00:00	46%	94%	79%	62%	1%
168-hour / 1-week	2035-10-22 00:00	34%	82%	46%	56%	5%
1-month	December	31%	65%	46%	53%	1%
3-month (year quarter)	Oct-Nov-Dec	27%	58%	34%	48%	3%

CEESA 2030 modified Scenario



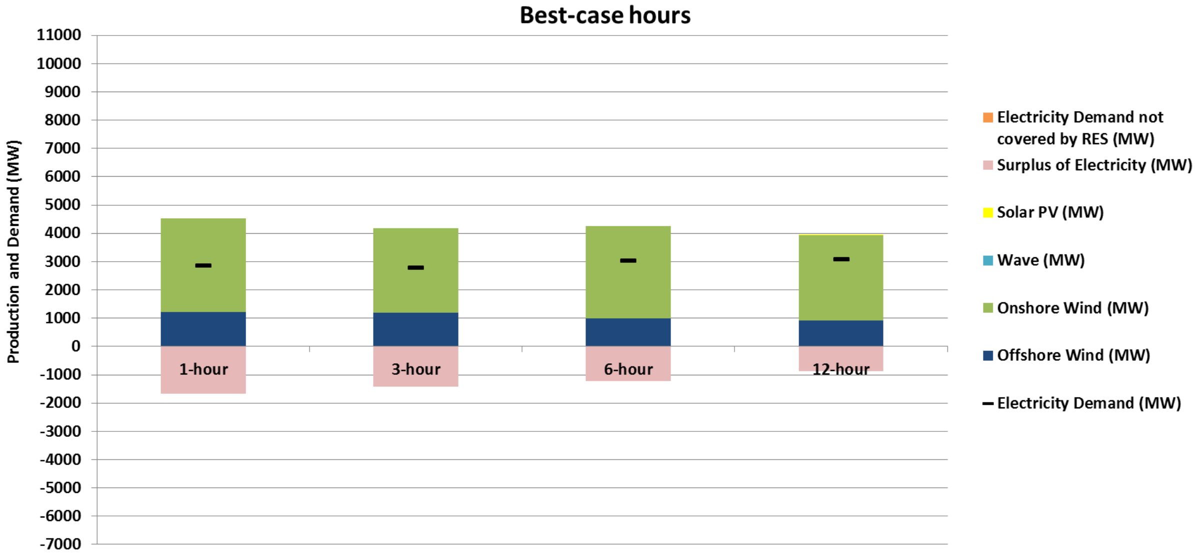


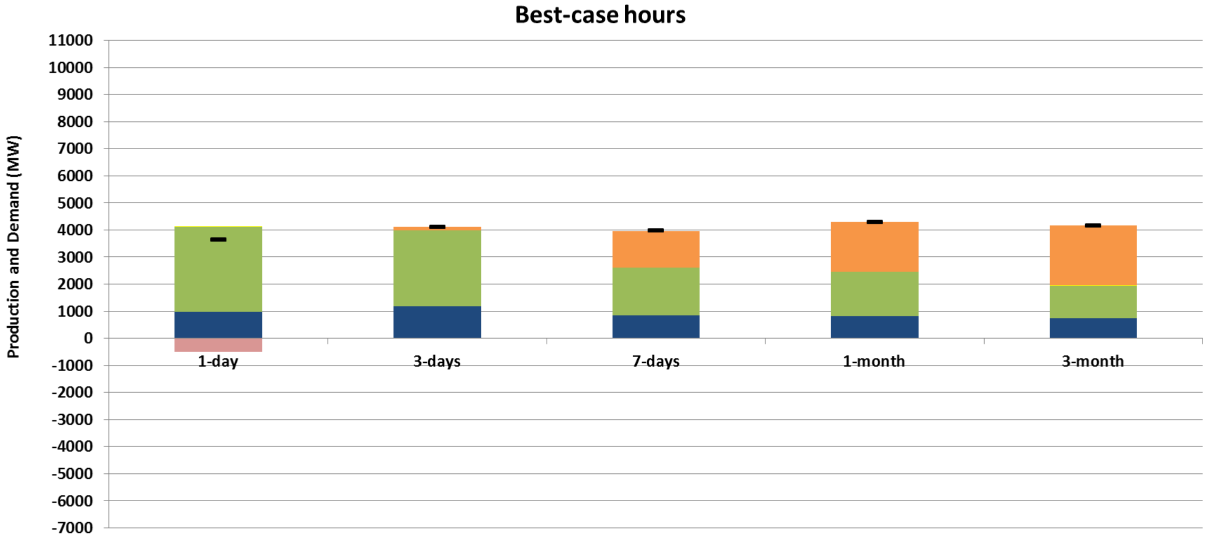
Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-06-02 13:00	77%	78%	90%	39%	58%
3-hour	2035-06-02 12:00	76%	78%	90%	39%	55%
6-hour	2035-06-02 12:00	71%	78%	90%	40%	39%
12-hour	2035-06-02 12:00	61%	90%	88%	30%	0%
24-hour / 1-day	2035-06-02 00:00	64%	99%	90%	55%	0%
72-hour / 3-day	2035-12-21 00:00	59%	94%	79%	62%	1%
168-hour / 1-week	2035-10-22 00:00	42%	82%	46%	56%	5%
1-month	December	37%	65%	46%	53%	1%
3-month (year quarter)	Oct-Nov-Dec	31%	58%	34%	48%	3%

1.1.4) Best periods: hours of maximum RES production and minimum electricity consumption

This case study identifies the time periods where the combined RES production is highest and electricity consumption is lowest.

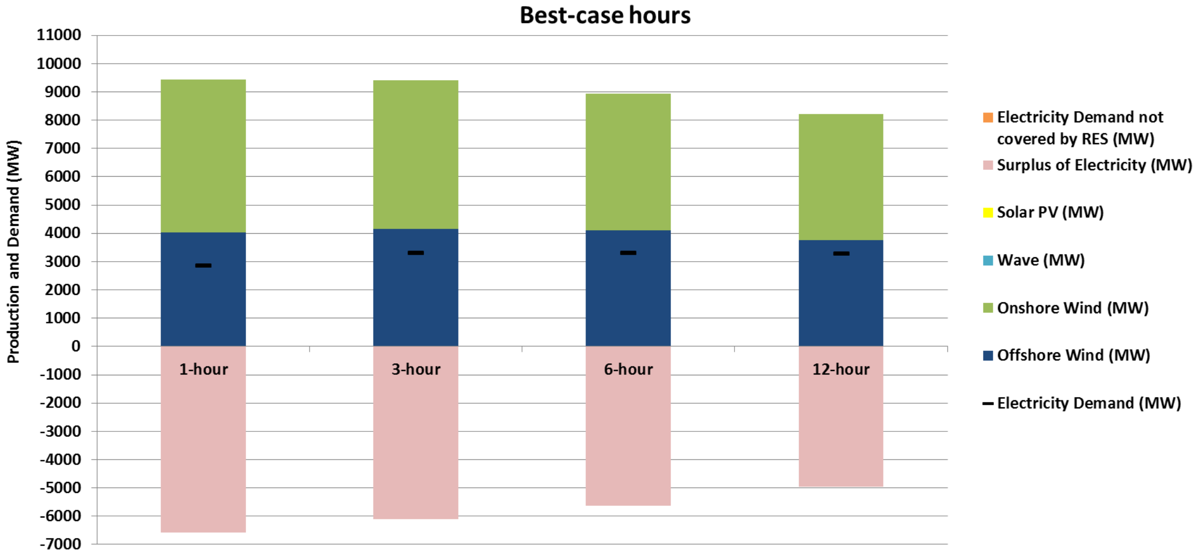
Year 2013

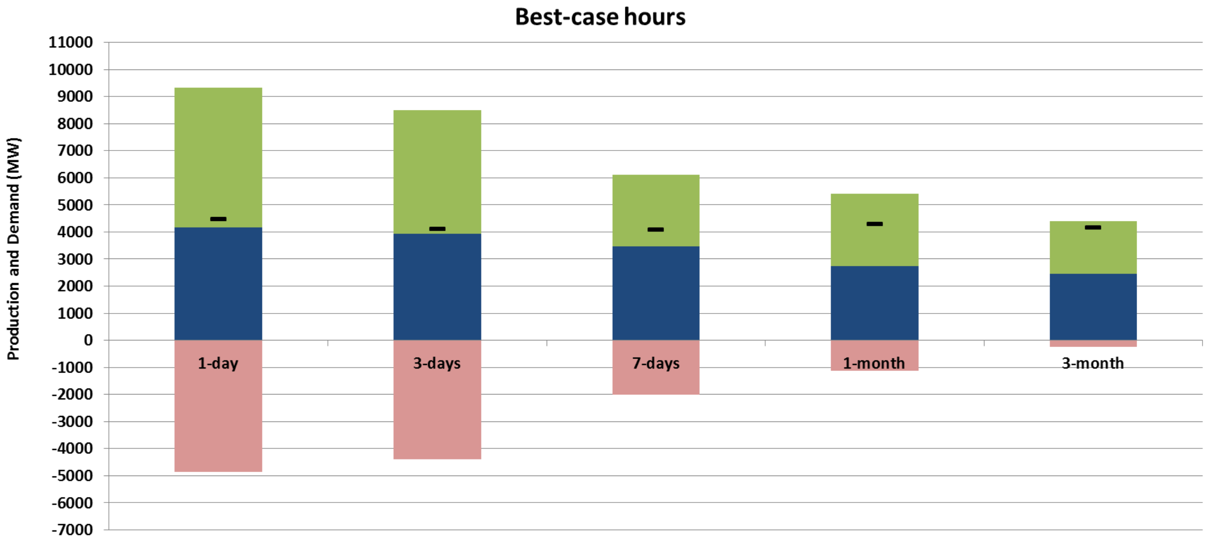




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-12-24 00:00	86%	96%	94%	0%	0%
3-hour	2035-12-24 00:00	79%	94%	85%	0%	0%
6-hour	2035-03-18 00:00	80%	78%	92%	0%	0%
12-hour	2035-03-18 00:00	75%	72%	85%	0%	5%
24-hour / 1-day	2035-03-18 00:00	78%	78%	88%	0%	5%
72-hour / 3-day	2035-12-21 00:00	76%	94%	79%	0%	1%
168-hour / 1-week	2035-12-24 00:00	49%	67%	50%	0%	1%
1-month	December	47%	65%	46%	0%	1%
3-month (year quarter)	Oct-Nov-Dec	37%	58%	34%	0%	3%

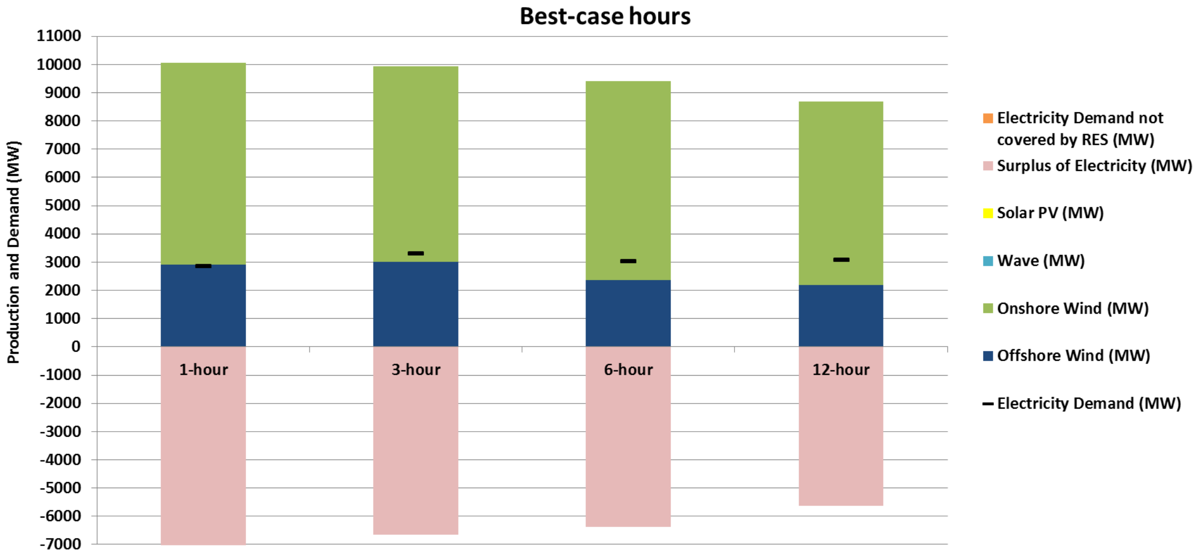
Ambitious Offshore Wind Scenario

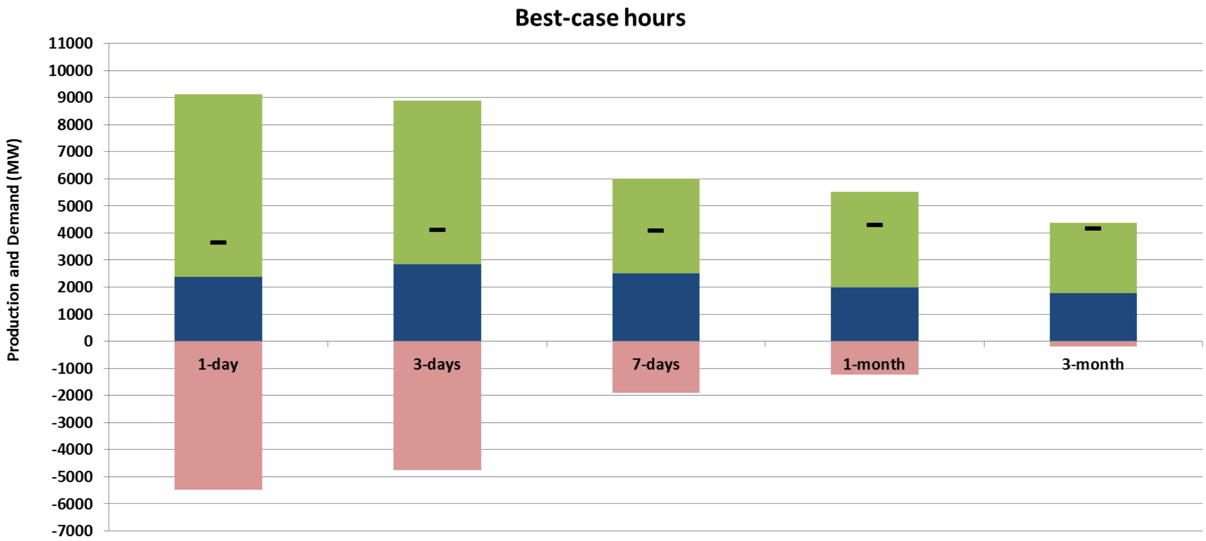




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-12-24 00:00	94%	96%	94%	0%	0%
3-hour	2035-12-21 03:00	94%	99%	91%	0%	0%
6-hour	2035-12-21 00:00	90%	97%	84%	0%	0%
12-hour	2035-12-01 00:00	82%	89%	77%	0%	0%
24-hour / 1-day	2035-12-21 00:00	93%	99%	90%	0%	0%
72-hour / 3-day	2035-12-21 00:00	85%	94%	79%	0%	0%
168-hour / 1-week	2035-10-22 00:00	61%	82%	46%	0%	0%
1-month	December	54%	65%	46%	0%	0%
3-month (year quarter)	Oct-Nov-Dec	44%	58%	34%	0%	0%

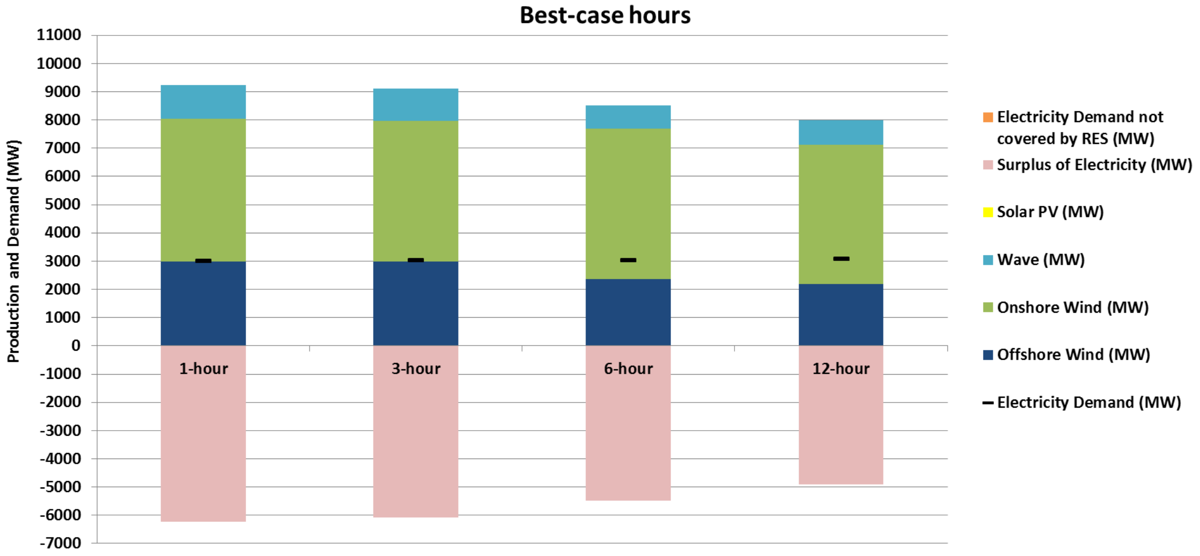
Ambitious Onshore Wind Scenario

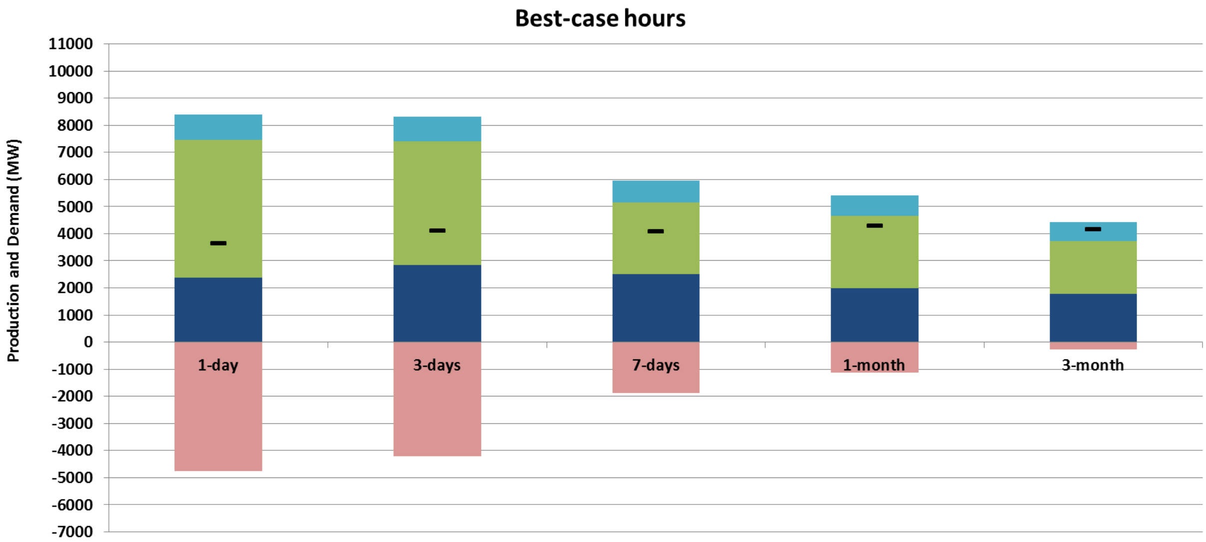




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-12-24 00:00	94%	96%	94%	0%	0%
3-hour	2035-12-21 03:00	93%	99%	91%	0%	0%
6-hour	2035-03-18 00:00	88%	78%	92%	0%	0%
12-hour	2035-03-18 00:00	81%	72%	85%	0%	0%
24-hour / 1-day	2035-03-18 00:00	85%	78%	88%	0%	0%
72-hour / 3-day	2035-12-21 00:00	83%	94%	79%	0%	0%
168-hour / 1-week	2035-10-22 00:00	56%	82%	46%	0%	0%
1-month	December	52%	65%	46%	0%	0%
3-month (year quarter)	Oct-Nov-Dec	41%	58%	34%	0%	0%

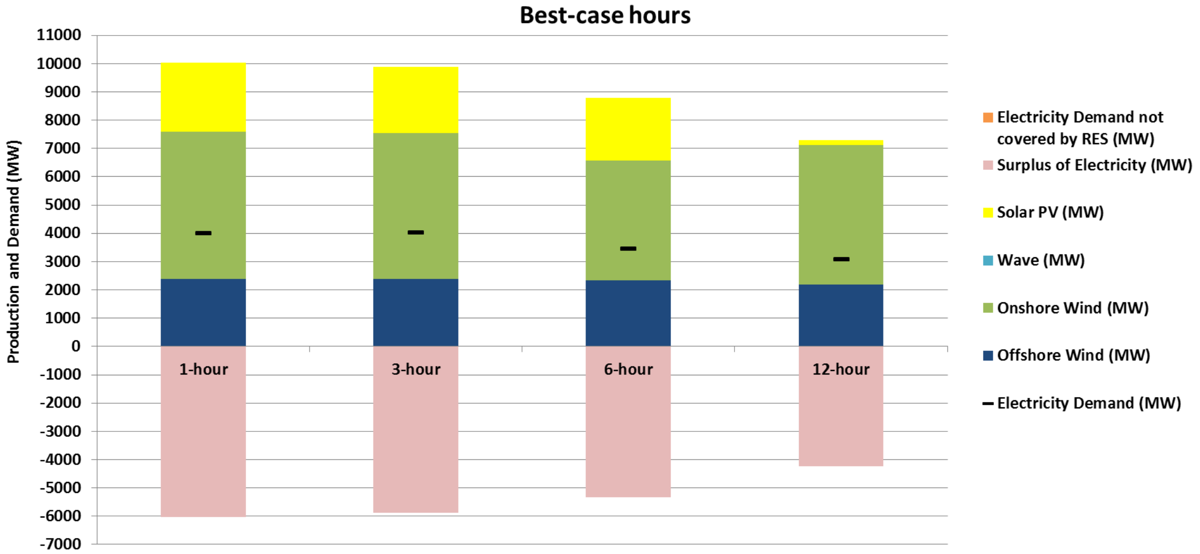
Ambitious Wave Scenario

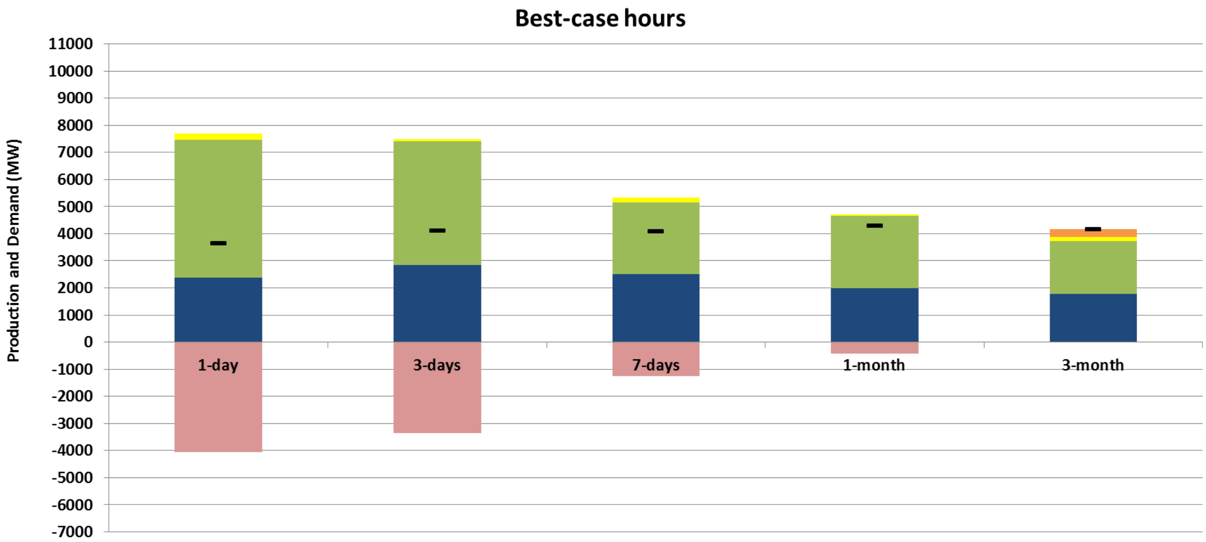




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-12-01 04:00	90%	98%	88%	81%	0%
3-hour	2035-12-01 03:00	89%	98%	87%	78%	0%
6-hour	2035-03-18 00:00	83%	78%	92%	57%	0%
12-hour	2035-03-18 00:00	78%	72%	85%	60%	0%
24-hour / 1-day	2035-03-18 00:00	82%	78%	88%	64%	0%
72-hour / 3-day	2035-12-21 00:00	81%	94%	79%	62%	0%
168-hour / 1-week	2035-10-22 00:00	58%	82%	46%	56%	0%
1-month	December	53%	65%	46%	53%	0%
3-month (year quarter)	Oct-Nov-Dec	43%	58%	34%	48%	0%

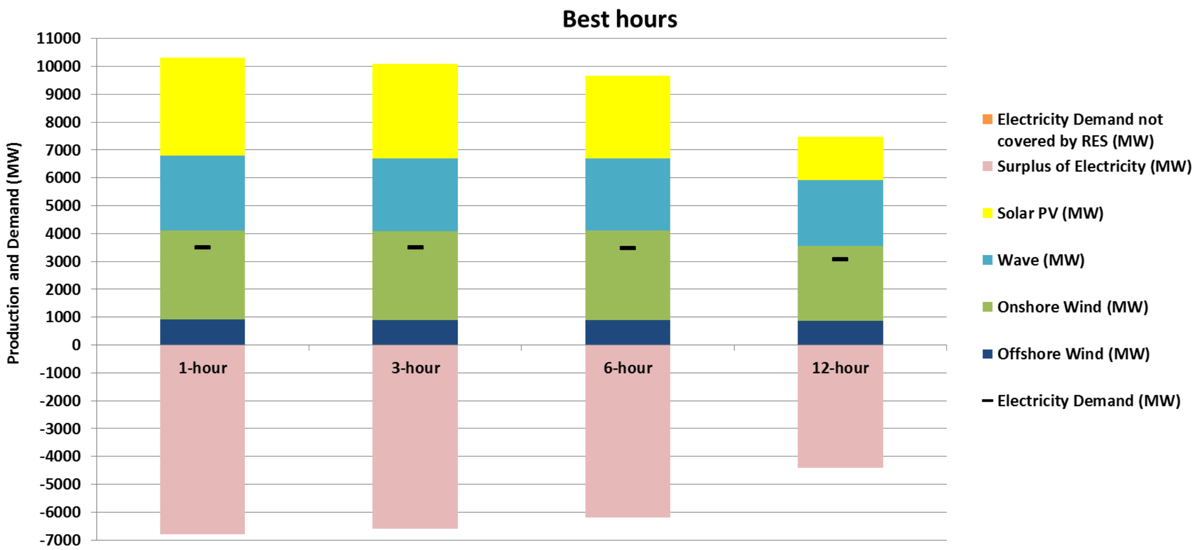
Ambitious Solar PV Scenario

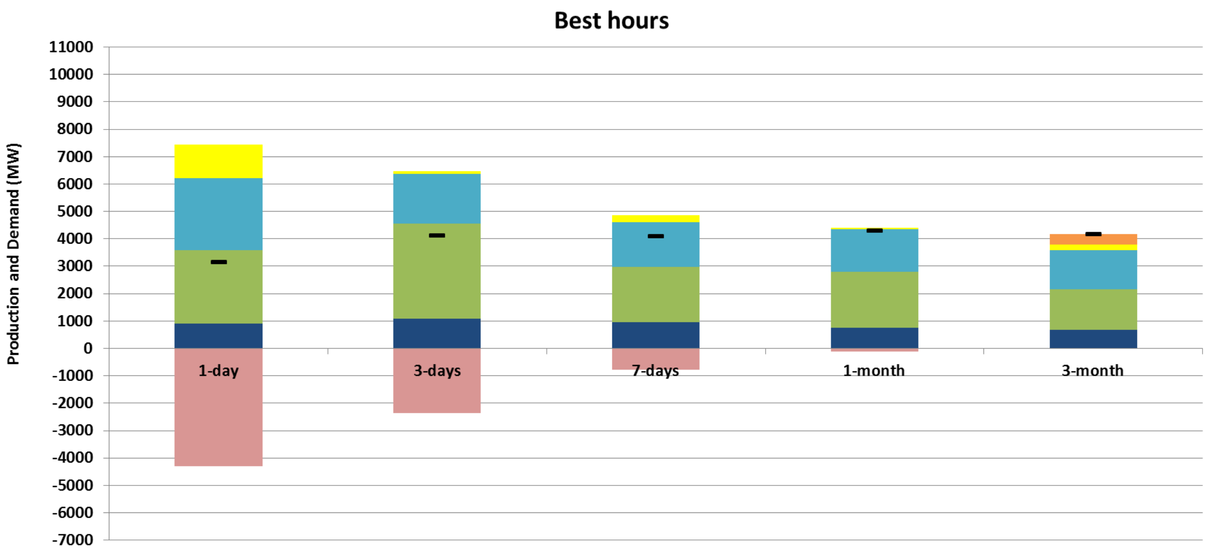




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-03-17 13:00	77%	78%	90%	0%	58%
3-hour	2035-03-17 12:00	76%	78%	90%	0%	55%
6-hour	2035-06-02 12:00	67%	77%	74%	0%	52%
12-hour	2035-03-18 00:00	56%	72%	85%	0%	5%
24-hour / 1-day	2035-03-18 00:00	59%	78%	88%	0%	5%
72-hour / 3-day	2035-12-21 00:00	57%	94%	79%	0%	1%
168-hour / 1-week	2035-10-22 00:00	41%	82%	46%	0%	5%
1-month	December	36%	65%	46%	0%	1%
3-month (year quarter)	Oct-Nov-Dec	30%	58%	34%	0%	3%

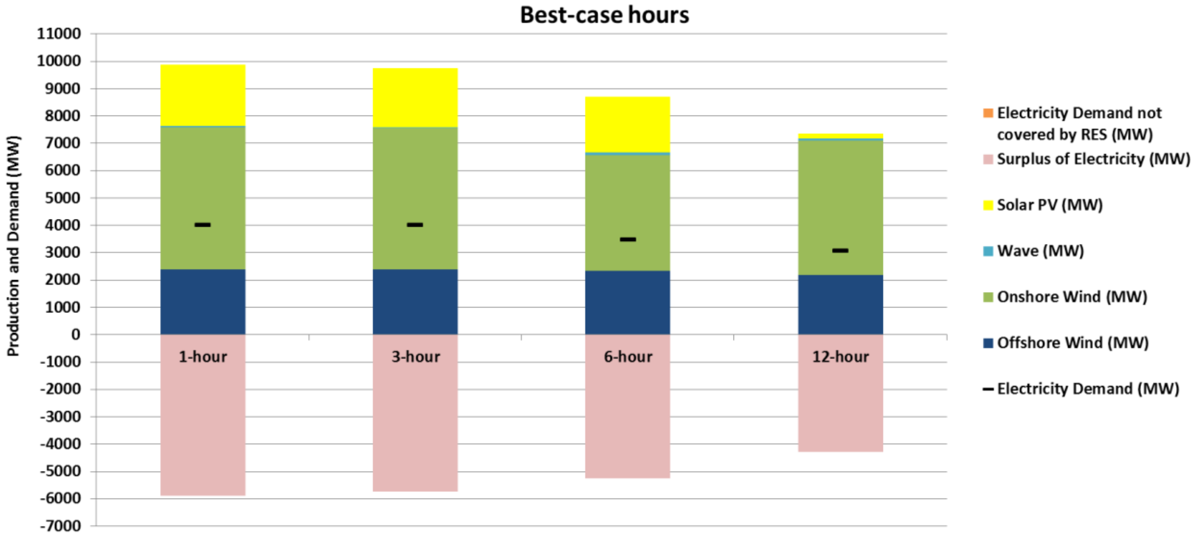
Combined RES Scenario

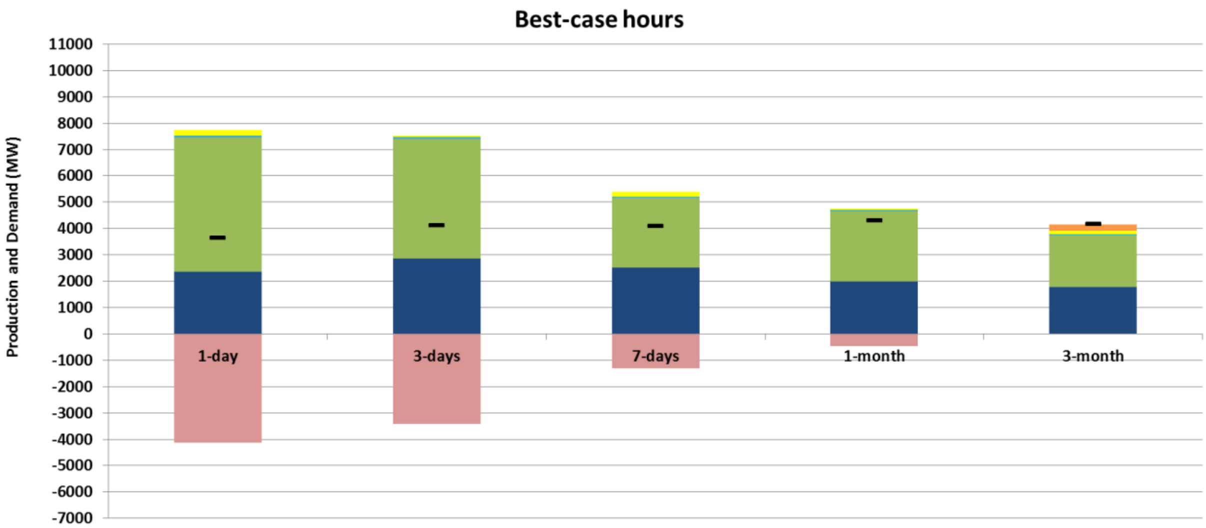




Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-06-02 13:00	73%	78%	73%	91%	62%
3-hour	2035-06-02 12:00	71%	76%	73%	90%	60%
6-hour	2035-06-02 12:00	68%	77%	74%	88%	52%
12-hour	2035-06-02 12:00	53%	73%	61%	81%	28%
24-hour / 1-day	2035-06-02 00:00	53%	78%	61%	90%	22%
72-hour / 3-day	2035-12-21 00:00	46%	94%	79%	62%	1%
168-hour / 1-week	2035-10-22 00:00	34%	82%	46%	56%	5%
1-month	December	31%	65%	46%	53%	1%
3-month (year quarter)	Oct-Nov-Dec	27%	58%	34%	48%	3%

CEESA 2030 modified Scenario





Capacity Credits (in % of Installed Capacity)						
Time-frames	Date & Hour	All RES Combined	Offshore wind	Onshore wind	Wave	PV Prod.
1-hour	2035-03-17 13:00	77%	78%	90%	39%	58%
3-hour	2035-03-17 12:00	76%	78%	90%	39%	55%
6-hour	2035-06-02 12:00	68%	77%	74%	88%	52%
12-hour	2035-03-18 00:00	57%	72%	85%	60%	5%
24-hour / 1-day	2035-03-18 00:00	60%	78%	88%	64%	5%
72-hour / 3-day	2035-12-21 00:00	59%	94%	79%	62%	1%
168-hour / 1-week	2035-10-22 00:00	42%	82%	46%	56%	5%
1-month	December	37%	65%	46%	53%	1%
3-month (year quarter)	Oct-Nov-Dec	31%	58%	34%	48%	3%

1.1.5) Capacity Credits Summary Tables based on "Approach A: Electricity-Only System"

With background values:

RES	Cf (h/y)	Cf (%)
Offshore Wind	3504	40%
Onshore Wind	2190	25%
Wave	2803	32%
Solar PV	964	11%

	Year 2013 Scenario [4.5 - 7.7 - 0 - 0.5 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 25%	89% ≤ CC ≤ 90%	79% ≤ CC ≤ 86%
12-hour to 24-hour	2% ≤ CC ≤ 3%	14% ≤ CC ≤ 23%	81% ≤ CC ≤ 84%	75% ≤ CC ≤ 78%
3-day to 1-week	12% ≤ CC ≤ 14%	12% ≤ CC ≤ 25%	51% ≤ CC ≤ 76%	49% ≤ CC ≤ 76%
1-month to 3-month	19% ≤ CC ≤ 27%	27% ≤ CC ≤ 27%	37% ≤ CC ≤ 47%	37% ≤ CC ≤ 47%

	CEESA2030-modified Scenario [10.7 - 12.5 - 0.3 - 3.8 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 20%	71% ≤ CC ≤ 77%	68% ≤ CC ≤ 77%
12-hour to 24-hour	3% ≤ CC ≤ 3%	12% ≤ CC ≤ 19%	61% ≤ CC ≤ 64%	57% ≤ CC ≤ 60%
3-day to 1-week	5% ≤ CC ≤ 12%	10% ≤ CC ≤ 20%	42% ≤ CC ≤ 59%	42% ≤ CC ≤ 59%
1-month to 3-month	16% ≤ CC ≤ 23%	22% ≤ CC ≤ 23%	31% ≤ CC ≤ 37%	31% ≤ CC ≤ 37%

	Ambitious Offshore Wind Scenario [14.8 - 12.5 - 0 - 0 TWh/y]			
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	1% ≤ CC ≤ 3%	9% ≤ CC ≤ 30%	98% ≤ CC ≤ 99%	90% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 4%	17% ≤ CC ≤ 27%	89% ≤ CC ≤ 93%	82% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 16%	15% ≤ CC ≤ 29%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 31%	31% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

	Ambitious Onshore Wind Scenario [10.7 - 16.6 - 0 - 0 TWh/y]			
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 28%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 94%
12-hour to 24-hour	2% ≤ CC ≤ 3%	15% ≤ CC ≤ 25%	89% ≤ CC ≤ 92%	81% ≤ CC ≤ 85%
3-day to 1-week	6% ≤ CC ≤ 15%	13% ≤ CC ≤ 27%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 21%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

	Ambitious Wave Scenario [10.7 - 12.5 - 4 - 0 TWh/y]			
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	3% ≤ CC ≤ 3%	8% ≤ CC ≤ 30%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 4%	16% ≤ CC ≤ 27%	81% ≤ CC ≤ 87%	78% ≤ CC ≤ 82%
3-day to 1-week	7% ≤ CC ≤ 16%	14% ≤ CC ≤ 28%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

	Ambitious Solar PV Scenario [10.7 - 12.5 - 0 - 4.2 TWh/y]			
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 19%	71% ≤ CC ≤ 77%	67% ≤ CC ≤ 77%
12-hour to 24-hour	2% ≤ CC ≤ 3%	11% ≤ CC ≤ 18%	60% ≤ CC ≤ 63%	56% ≤ CC ≤ 59%
3-day to 1-week	5% ≤ CC ≤ 12%	10% ≤ CC ≤ 20%	41% ≤ CC ≤ 57%	41% ≤ CC ≤ 57%
1-month to 3-month	16% ≤ CC ≤ 22%	21% ≤ CC ≤ 22%	30% ≤ CC ≤ 36%	30% ≤ CC ≤ 36%

	Lund (2006) Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]			
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 4%	7% ≤ CC ≤ 18%	68% ≤ CC ≤ 73%	68% ≤ CC ≤ 73%
12-hour to 24-hour	3% ≤ CC ≤ 3%	10% ≤ CC ≤ 16%	53% ≤ CC ≤ 53%	53% ≤ CC ≤ 53%
3-day to 1-week	5% ≤ CC ≤ 11%	8% ≤ CC ≤ 17%	34% ≤ CC ≤ 46%	34% ≤ CC ≤ 46%
1-month to 3-month	15% ≤ CC ≤ 20%	19% ≤ CC ≤ 20%	27% ≤ CC ≤ 31%	27% ≤ CC ≤ 31%

	Offshore Wind - Only Scenario [27.5 - 0 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	1% ≤ CC ≤ 3%	15% ≤ CC ≤ 37%	100% ≤ CC ≤ 100%	97% ≤ CC ≤ 98%
12-hour to 24-hour	5% ≤ CC ≤ 6%	23% ≤ CC ≤ 36%	92% ≤ CC ≤ 99%	87% ≤ CC ≤ 92%
3-day to 1-week	9% ≤ CC ≤ 15%	22% ≤ CC ≤ 38%	82% ≤ CC ≤ 94%	82% ≤ CC ≤ 94%
1-month to 3-month	30% ≤ CC ≤ 37%	37% ≤ CC ≤ 37%	58% ≤ CC ≤ 65%	58% ≤ CC ≤ 65%

	Onshore Wind - Only Scenario [0 - 27.1 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	1% ≤ CC ≤ 1%	5% ≤ CC ≤ 24%	98% ≤ CC ≤ 100%	92% ≤ CC ≤ 94%
12-hour to 24-hour	1% ≤ CC ≤ 2%	12% ≤ CC ≤ 21%	88% ≤ CC ≤ 90%	85% ≤ CC ≤ 88%
3-day to 1-week	5% ≤ CC ≤ 12%	10% ≤ CC ≤ 23%	50% ≤ CC ≤ 79%	50% ≤ CC ≤ 79%
1-month to 3-month	17% ≤ CC ≤ 17%	26% ≤ CC ≤ 26%	34% ≤ CC ≤ 46%	34% ≤ CC ≤ 46%

	Wave - Only Scenario [0 - 0 - 27.1 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	0% ≤ CC ≤ 0%	6% ≤ CC ≤ 34%	94% ≤ CC ≤ 100%	94% ≤ CC ≤ 99%
12-hour to 24-hour	0% ≤ CC ≤ 0%	17% ≤ CC ≤ 29%	84% ≤ CC ≤ 90%	84% ≤ CC ≤ 90%
3-day to 1-week	3% ≤ CC ≤ 6%	14% ≤ CC ≤ 26%	63% ≤ CC ≤ 71%	63% ≤ CC ≤ 71%
1-month to 3-month	26% ≤ CC ≤ 29%	29% ≤ CC ≤ 32%	48% ≤ CC ≤ 53%	48% ≤ CC ≤ 53%

In the wave-only scenario it is remarkable that there is no wave energy production during some of the *worst periods* of the analysis. This is due to the fact that:

- The worst 1-hour to 6-hour occur on 21st and 22nd February (2013), where there is no wave production due to too small, almost none, waves in Hanstholm and Horns Rev 3 (Hm0<0.5m)
- The worst 12-hour to 24-hour occur on 6th December (2013), where there is no wave production due to too high waves in Hanstholm (3.5m<Hm0<6.0m) and Horns Rev 3 (3.5m<Hm0<8.5m)

	Solar PV - Only Scenario [0 - 0 - 0 - 27.9 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	0% ≤ CC ≤ 0%	0% ≤ CC ≤ 7%	70% ≤ CC ≤ 82%	70% ≤ CC ≤ 82%
12-hour to 24-hour	0% ≤ CC ≤ 0%	2% ≤ CC ≤ 2%	30% ≤ CC ≤ 36%	30% ≤ CC ≤ 36%
3-day to 1-week	1% ≤ CC ≤ 1%	1% ≤ CC ≤ 2%	27% ≤ CC ≤ 29%	27% ≤ CC ≤ 29%
1-month to 3-month	2% ≤ CC ≤ 3%	2% ≤ CC ≤ 6%	18% ≤ CC ≤ 20%	18% ≤ CC ≤ 20%

	Heide et.al. (Århus) Scenario [0 - 21.7 - 0 - 5.6 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	1% ≤ CC ≤ 2%	6% ≤ CC ≤ 15%	75% ≤ CC ≤ 83%	72% ≤ CC ≤ 78%
12-hour to 24-hour	1% ≤ CC ≤ 2%	9% ≤ CC ≤ 14%	58% ≤ CC ≤ 60%	56% ≤ CC ≤ 58%
3-day to 1-week	7% ≤ CC ≤ 9%	7% ≤ CC ≤ 16%	32% ≤ CC ≤ 52%	32% ≤ CC ≤ 50%
1-month to 3-month	12% ≤ CC ≤ 19%	18% ≤ CC ≤ 19%	23% ≤ CC ≤ 30%	21% ≤ CC ≤ 30%

➔ ENS projects the following capacity factors for offshore wind, onshore wind, wave and solar PV technologies for year 2035 (Energistyrelsen, 2014).

RES	Cf (%)
Offshore Wind	47%
Onshore Wind	35%
Wave	0%
Solar PV	10%

However, as distribution data are from year 2013, and they have not been updated to ENS2035 projected values, with the installed capacity projected in ENS Wind 2035 Scenario RES production are smaller than those estimated by ENS. Calculations should be redone accordingly.

	ENS Wind 2035 Scenario [17.6 - 7.6 - 0 - 1.5 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	3% ≤ CC ≤ 4%	10% ≤ CC ≤ 27%	84% ≤ CC ≤ 84%	78% ≤ CC ≤ 81%
12-hour to 24-hour	3% ≤ CC ≤ 4%	16% ≤ CC ≤ 26%	76% ≤ CC ≤ 81%	72% ≤ CC ≤ 81%
3-day to 1-week	7% ≤ CC ≤ 16%	14% ≤ CC ≤ 27%	58% ≤ CC ≤ 75%	58% ≤ CC ≤ 75%
1-month to 3-month	22% ≤ CC ≤ 28%	28% ≤ CC ≤ 28%	42% ≤ CC ≤ 49%	42% ≤ CC ≤ 49%

2) Modellin Tool: EnergyPLAN Model

2.1) ELECTRICITY-ONLY SYSTEM APPROACH

Some scenarios:

	EnergyPLAN - Ambitious Offshore Wind Scenario [14.7 - 12.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	1% ≤ CC ≤ 3%	9% ≤ CC ≤ 30%	98% ≤ CC ≤ 99%	94% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 3%	17% ≤ CC ≤ 27%	89% ≤ CC ≤ 93%	89% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 13%	15% ≤ CC ≤ 29%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 23%	30% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

	EnergyPLAN - Ambitious Onshore Wind Scenario [10.6 - 16.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	1% ≤ CC ≤ 2%	8% ≤ CC ≤ 28%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 97%
12-hour to 24-hour	2% ≤ CC ≤ 3%	15% ≤ CC ≤ 25%	89% ≤ CC ≤ 92%	89% ≤ CC ≤ 92%
3-day to 1-week	6% ≤ CC ≤ 8%	13% ≤ CC ≤ 27%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 21%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

	EnergyPLAN - Ambitious Wave Scenario [10.6 - 12.6 - 4 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	3% ≤ CC ≤ 3%	8% ≤ CC ≤ 29%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 4%	16% ≤ CC ≤ 26%	81% ≤ CC ≤ 88%	79% ≤ CC ≤ 88%
3-day to 1-week	7% ≤ CC ≤ 8%	14% ≤ CC ≤ 28%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 22%	30% ≤ CC ≤ 30%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

	EnergyPLAN - Ambitious Solar PV Scenario [10.6 - 12.6 - 0 - 4.1 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	1% ≤ CC ≤ 3%	8% ≤ CC ≤ 21%	75% ≤ CC ≤ 82%	75% ≤ CC ≤ 82%
12-hour to 24-hour	2% ≤ CC ≤ 3%	12% ≤ CC ≤ 19%	64% ≤ CC ≤ 67%	63% ≤ CC ≤ 67%
3-day to 1-week	5% ≤ CC ≤ 12%	10% ≤ CC ≤ 21%	44% ≤ CC ≤ 61%	44% ≤ CC ≤ 61%
1-month to 3-month	17% ≤ CC ≤ 23%	22% ≤ CC ≤ 23%	32% ≤ CC ≤ 38%	32% ≤ CC ≤ 38%

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	0.00	4.08	2.19	1.84	11.37	3.41	0.00				
Max. MW	3824	3045	5767	0	3445	450	236	4445	3326	0	0	0	-794	794

	EnergyPLAN - Lund (2006) Scenario [4.1 - 9.5 - 8.1 - 5.5 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 3%	7% ≤ CC ≤ 19%	73% ≤ CC ≤ 78%	73% ≤ CC ≤ 78%
12-hour to 24-hour	3% ≤ CC ≤ 4%	11% ≤ CC ≤ 18%	57% ≤ CC ≤ 57%	57% ≤ CC ≤ 57%
3-day to 1-week	5% ≤ CC ≤ 11%	9% ≤ CC ≤ 18%	37% ≤ CC ≤ 49%	37% ≤ CC ≤ 49%
1-month to 3-month	16% ≤ CC ≤ 21%	20% ≤ CC ≤ 21%	29% ≤ CC ≤ 34%	29% ≤ CC ≤ 34%

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	4.11	9.58	8.16	5.48	2.24	1.84	11.06	3.16	0.00				
Max. MW	3824	1172	4376	2930	4624	450	236	4445	3003	0	0	0	-608	608

CEESA2030modified - Case study I (=Case study II = Case Study III = IV)

	EnergyPLAN - CEESA2030-modified Scenario Case study - I [10.6 - 12.6 - 0.3 - 3.8 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	1% ≤ CC ≤ 3%	8% ≤ CC ≤ 21%	75% ≤ CC ≤ 81%	75% ≤ CC ≤ 81%
12-hour to 24-hour	1% ≤ CC ≤ 3%	12% ≤ CC ≤ 20%	65% ≤ CC ≤ 68%	64% ≤ CC ≤ 68%
3-day to 1-week	6% ≤ CC ≤ 13%	11% ≤ CC ≤ 21%	44% ≤ CC ≤ 62%	44% ≤ CC ≤ 62%
1-month to 3-month	17% ≤ CC ≤ 24%	23% ≤ CC ≤ 24%	32% ≤ CC ≤ 39%	32% ≤ CC ≤ 39%

2.2) INTEGRATED ENERGY SYSTEMS APPROACH: INCLUDING ALL ELECTRICITY DEMANDS IN THE SYSTEM

2.2.1) Case study I: Technical Strategy 3 and Interconnections Capacity of 0MW

CEESA2030modified

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	0.32	3.76	2.19	1.84	11.34	3.49	0.00				
Max. MW	3824	3045	5767	114	3175	450	236	4445	3339	0	0	0	-802	802

	EnergyPLAN - CEESA2030-modified Scenario Case study - I [10.6 - 12.6 - 0.3 - 3.8 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 7%	61% ≤ CC ≤ 70%	75% ≤ CC ≤ 81%	72% ≤ CC ≤ 81%
12-hour to 24-hour	1% ≤ CC ≤ 7%	50% ≤ CC ≤ 53%	65% ≤ CC ≤ 68%	61% ≤ CC ≤ 64%
3-day to 1-week	8% ≤ CC ≤ 14%	14% ≤ CC ≤ 17%	44% ≤ CC ≤ 62%	44% ≤ CC ≤ 62%
1-month to 3-month	17% ≤ CC ≤ 24%	23% ≤ CC ≤ 24%	32% ≤ CC ≤ 39%	32% ≤ CC ≤ 39%

Ambitious Offshore Wind

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	14.76	12.63	0.00	0.00	2.15	1.84	11.22	4.58	0.00				
Max. MW	3824	4209	5767	0	0	450	236	4445	4039	0	0	0	-1026	1026

	EnergyPLAN - Ambitious Offshore Wind Scenario - Case study I [14.7 - 12.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	4% ≤ CC ≤ 6%	77% ≤ CC ≤ 91%	98% ≤ CC ≤ 99%	90% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 3%	40% ≤ CC ≤ 59%	89% ≤ CC ≤ 93%	87% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 22%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Ambitious Onshore Wind

Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
21.85	10.68	16.70	0.00	0.00	2.12	1.84	11.42	4.65	0.00				
3824	3045	7630	0	0	450	236	4445	4029	0	0	0	-1051	1051

	EnergyPLAN - Ambitious Onshore Wind Scenario - Case study I [10.6 - 16.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	3% ≤ CC ≤ 5%	75% ≤ CC ≤ 90%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 94%
12-hour to 24-hour	2% ≤ CC ≤ 3%	38% ≤ CC ≤ 55%	89% ≤ CC ≤ 92%	86% ≤ CC ≤ 92%
3-day to 1-week	6% ≤ CC ≤ 18%	18% ≤ CC ≤ 21%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 29%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Ambitious Wave

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	4.05	0.00	2.16	1.84	11.07	4.63	0.00				
Max. MW	3824	3045	5767	1455	0	450	236	4445	3878	0	0	0	-979	979

	EnergyPLAN - Ambitious Wave Scenario - Case study I [10.6 - 12.6 - 4 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	3% ≤ CC ≤ 5%	75% ≤ CC ≤ 79%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 5%	42% ≤ CC ≤ 70%	81% ≤ CC ≤ 88%	78% ≤ CC ≤ 88%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 24%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 30%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Ambitious Solar PV

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	0.00	4.08	2.19	1.84	11.37	3.41	0.00				
Max. MW	3824	3045	5767	0	3445	450	236	4445	3326	0	0	0	-794	794

	EnergyPLAN - Ambitious Solar PV Scenario - Case study I [10.6 - 12.6 - 0 - 4.1 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 7%	60% ≤ CC ≤ 71%	75% ≤ CC ≤ 82%	71% ≤ CC ≤ 82%
12-hour to 24-hour	1% ≤ CC ≤ 4%	49% ≤ CC ≤ 52%	64% ≤ CC ≤ 67%	59% ≤ CC ≤ 63%
3-day to 1-week	8% ≤ CC ≤ 14%	14% ≤ CC ≤ 16%	44% ≤ CC ≤ 61%	44% ≤ CC ≤ 61%
1-month to 3-month	17% ≤ CC ≤ 23%	22% ≤ CC ≤ 23%	32% ≤ CC ≤ 38%	32% ≤ CC ≤ 38%

Combined RES

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	4.11	9.58	8.16	5.48	2.24	1.84	11.06	3.16	0.00				
Max. MW	3824	1172	4376	2930	4624	450	236	4445	3003	0	0	0	-608	608

	EnergyPLAN - Lund (2006) Scenario - Case study I [4.1 - 9.5 - 8.1 - 5.5 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 7%	55% ≤ CC ≤ 65%	73% ≤ CC ≤ 78%	73% ≤ CC ≤ 78%
12-hour to 24-hour	3% ≤ CC ≤ 6%	30% ≤ CC ≤ 48%	57% ≤ CC ≤ 57%	57% ≤ CC ≤ 57%
3-day to 1-week	8% ≤ CC ≤ 13%	18% ≤ CC ≤ 33%	37% ≤ CC ≤ 49%	32% ≤ CC ≤ 49%
1-month to 3-month	16% ≤ CC ≤ 21%	20% ≤ CC ≤ 21%	29% ≤ CC ≤ 34%	24% ≤ CC ≤ 26%

2.2.2) Case study II and III: Technical Strategy 3 and Interconnections Capacity of 5820 MW and 9780MW, respectively

Only results for Case II are shown here as they are the same as for Case III.

CEESA2030modified

CEESA 2030 - modified.t	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	0.32	3.76	2.19	1.84	11.43	4.47	0.00				
Max. MW	3824	3045	5767	114	3175	450	236	4445	3373	0	-1334	0	-1334	0

	EnergyPLAN - CEESA2030 modified Scenario - Case study II [10.6 - 12.6 - 0.3 - 3.8 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 7%	30% ≤ CC ≤ 33%	75% ≤ CC ≤ 81%	72% ≤ CC ≤ 81%
12-hour to 24-hour	1% ≤ CC ≤ 4%	24% ≤ CC ≤ 30%	65% ≤ CC ≤ 68%	61% ≤ CC ≤ 68%
3-day to 1-week	8% ≤ CC ≤ 14%	14% ≤ CC ≤ 17%	44% ≤ CC ≤ 62%	44% ≤ CC ≤ 62%
1-month to 3-month	17% ≤ CC ≤ 24%	23% ≤ CC ≤ 24%	32% ≤ CC ≤ 39%	32% ≤ CC ≤ 39%

Ambitious Offshore Wind

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	14.76	12.63	0.00	0.00	2.15	1.84	11.32	5.51	0.00				
Max. MW	3824	4209	5767	0	0	450	236	4445	4071	0	-1535	0	-1535	0

	EnergyPLAN - Ambitious Offshore Wind Scenario - Case study II [14.7 - 12.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	4% ≤ CC ≤ 6%	39% ≤ CC ≤ 43%	98% ≤ CC ≤ 99%	90% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 3%	33% ≤ CC ≤ 40%	89% ≤ CC ≤ 93%	87% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 22%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Ambitious Onshore Wind

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	16.70	0.00	0.00	2.12	1.84	11.52	5.59	0.00				
Max. MW	3824	3045	7630	0	0	450	236	4445	4058	0	-1532	0	-1532	0

	EnergyPLAN - Ambitious Onshore Wind Scenario - Case study II[10.6 - 16.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	3% ≤ CC ≤ 5%	37% ≤ CC ≤ 41%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 97%
12-hour to 24-hour	2% ≤ CC ≤ 3%	31% ≤ CC ≤ 38%	89% ≤ CC ≤ 92%	86% ≤ CC ≤ 92%
3-day to 1-week	6% ≤ CC ≤ 18%	18% ≤ CC ≤ 21%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 29%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Ambitious Wave

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	4.05	0.00	2.16	1.84	11.17	5.51	0.00				
Max. MW	3824	3045	5767	1455	0	450	236	4445	3909	0	-1482	0	-1482	0

	EnergyPLAN - Ambitious Wave Scenario - Case study II [10.6 - 12.6 - 4 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	3% ≤ CC ≤ 5%	43% ≤ CC ≤ 47%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 5%	34% ≤ CC ≤ 42%	81% ≤ CC ≤ 88%	78% ≤ CC ≤ 88%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 24%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 30%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Ambitious Solar PV

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	0.00	4.08	2.19	1.84	11.47	4.40	0.00				
Max. MW	3824	3045	5767	0	3445	450	236	4445	3360	0	-1328	0	-1328	0

	EnergyPLAN - Ambitious Solar PV Scenario - Case study II [10.6 - 12.6 - 0 - 4.1 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 7%	30% ≤ CC ≤ 32%	75% ≤ CC ≤ 82%	71% ≤ CC ≤ 82%
12-hour to 24-hour	1% ≤ CC ≤ 4%	23% ≤ CC ≤ 29%	64% ≤ CC ≤ 67%	59% ≤ CC ≤ 67%
3-day to 1-week	8% ≤ CC ≤ 14%	14% ≤ CC ≤ 16%	44% ≤ CC ≤ 61%	44% ≤ CC ≤ 61%
1-month to 3-month	17% ≤ CC ≤ 23%	22% ≤ CC ≤ 23%	32% ≤ CC ≤ 38%	32% ≤ CC ≤ 38%

Combined RES

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	4.11	9.58	8.16	5.48	2.24	1.84	11.11	4.21	0.00				
Max. MW	3824	1172	4376	2930	4624	450	236	4445	3041	0	-1182	0	-1182	0

	EnergyPLAN - Lund (2006) Scenario - Case study II [4.1 - 9.5 - 8.1 - 5.5 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 7%	33% ≤ CC ≤ 35%	73% ≤ CC ≤ 78%	73% ≤ CC ≤ 78%
12-hour to 24-hour	3% ≤ CC ≤ 6%	23% ≤ CC ≤ 30%	57% ≤ CC ≤ 57%	57% ≤ CC ≤ 57%
3-day to 1-week	8% ≤ CC ≤ 13%	13% ≤ CC ≤ 18%	37% ≤ CC ≤ 49%	37% ≤ CC ≤ 49%
1-month to 3-month	16% ≤ CC ≤ 21%	20% ≤ CC ≤ 21%	29% ≤ CC ≤ 34%	26% ≤ CC ≤ 29%

2.2.3) Case study IV: Economic Strategy with Interconnections Capacity of 0MW

CEESA2030modified

CEESA 2030 - modified.t:	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	0.32	3.76	0.01	1.84	7.16	6.83	0.00				
Max. MW	3824	3045	5767	114	3175	450	236	2500	5869	0	9	14	0	-5

	EnergyPLAN - CEESA2030 modified Scenario - Case study IV [10.6 - 12.6 - 0.3 - 3.8 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 15%	15% ≤ CC ≤ 33%	75% ≤ CC ≤ 81%	72% ≤ CC ≤ 81%
12-hour to 24-hour	5% ≤ CC ≤ 7%	24% ≤ CC ≤ 30%	65% ≤ CC ≤ 68%	64% ≤ CC ≤ 64%
3-day to 1-week	13% ≤ CC ≤ 14%	13% ≤ CC ≤ 18%	44% ≤ CC ≤ 62%	44% ≤ CC ≤ 62%
1-month to 3-month	17% ≤ CC ≤ 24%	23% ≤ CC ≤ 24%	32% ≤ CC ≤ 39%	32% ≤ CC ≤ 39%

Ambitious Offshore Wind

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	14.76	12.63	0.00	0.00	0.02	1.84	7.18	7.76	0.00				
Max. MW	3824	4209	5767	0	0	450	236	2500	5869	0	8	13	0	-4

	EnergyPLAN - Ambitious Offshore Wind Scenario - Case study IV [14.7 - 12.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	3% ≤ CC ≤ 22%	22% ≤ CC ≤ 43%	98% ≤ CC ≤ 99%	89% ≤ CC ≤ 97%
12-hour to 24-hour	3% ≤ CC ≤ 3%	33% ≤ CC ≤ 40%	89% ≤ CC ≤ 93%	87% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 19%	17% ≤ CC ≤ 21%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Ambitious Onshore Wind

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	16.70	0.00	0.00	0.02	1.84	7.30	7.92	0.00				
Max. MW	3824	3045	7630	0	0	450	236	2500	5869	0	9	13	0	-5

	EnergyPLAN - Ambitious Onshore Wind Scenario - Case study IV [10.6 - 16.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 19%	17% ≤ CC ≤ 41%	98% ≤ CC ≤ 99%	94% ≤ CC ≤ 97%
12-hour to 24-hour	2% ≤ CC ≤ 3%	31% ≤ CC ≤ 38%	89% ≤ CC ≤ 92%	81% ≤ CC ≤ 92%
3-day to 1-week	6% ≤ CC ≤ 18%	15% ≤ CC ≤ 20%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 29%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Ambitious Wave

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	4.05	0.00	0.02	1.84	7.07	7.70	0.00				
Max. MW	3824	3045	5767	1455	0	450	236	2500	5869	0	8	13	0	-4

	EnergyPLAN - Ambitious Wave Scenario - Case study IV [10.6 - 12.6 - 4 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	3% ≤ CC ≤ 5%	43% ≤ CC ≤ 47%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 5%	34% ≤ CC ≤ 42%	81% ≤ CC ≤ 88%	78% ≤ CC ≤ 88%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 24%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 30%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Ambitious Solar PV

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	0.00	4.08	0.01	1.84	7.17	6.79	0.00				
Max. MW	3824	3045	5767	0	3445	450	236	2500	5869	0	10	14	0	-5

	EnergyPLAN - Ambitious Solar PV Scenario - Case study IV [10.6 - 12.6 - 0 - 4.1 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 15%	15% ≤ CC ≤ 32%	75% ≤ CC ≤ 82%	71% ≤ CC ≤ 82%
12-hour to 24-hour	5% ≤ CC ≤ 7%	23% ≤ CC ≤ 29%	64% ≤ CC ≤ 67%	63% ≤ CC ≤ 63%
3-day to 1-week	5% ≤ CC ≤ 14%	13% ≤ CC ≤ 18%	44% ≤ CC ≤ 61%	44% ≤ CC ≤ 61%
1-month to 3-month	17% ≤ CC ≤ 23%	22% ≤ CC ≤ 23%	32% ≤ CC ≤ 38%	32% ≤ CC ≤ 38%

Combined RES

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	4.11	9.58	8.16	5.48	0.01	1.84	6.93	6.49	0.00				
Max. MW	3824	1172	4376	2930	4624	450	236	2500	5869	0	9	14	0	-5

	EnergyPLAN - Lund (2006) Scenario - Case study IV [4.1 - 9.5 - 8.1 - 5.5 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 15%	15% ≤ CC ≤ 35%	73% ≤ CC ≤ 78%	73% ≤ CC ≤ 78%
12-hour to 24-hour	5% ≤ CC ≤ 6%	23% ≤ CC ≤ 30%	57% ≤ CC ≤ 57%	57% ≤ CC ≤ 57%
3-day to 1-week	8% ≤ CC ≤ 13%	20% ≤ CC ≤ 23%	37% ≤ CC ≤ 49%	37% ≤ CC ≤ 49%
1-month to 3-month	16% ≤ CC ≤ 21%	20% ≤ CC ≤ 21%	29% ≤ CC ≤ 34%	29% ≤ CC ≤ 34%

2.2.4) Case study V and VI: Economic Strategy with Interconnections Capacity of 5820 MW and 9780MW, respectively

Only results for Case V are shown here as they are the same as for Case VI.

CEESA2030modified

CEESA 2030 - modified.t	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	0.32	3.76	0.01	1.84	8.01	5.86	0.00				
Max. MW	3824	3045	5767	114	3175	450	236	2500	5869	0	-1811	1889	-3688	-12

	EnergyPLAN - CEESA2030 modified Scenario - Case study V [10.6 - 12.6 - 0.3 - 3.8 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 8%	13% ≤ CC ≤ 33%	75% ≤ CC ≤ 81%	72% ≤ CC ≤ 81%
12-hour to 24-hour	4% ≤ CC ≤ 5%	24% ≤ CC ≤ 30%	65% ≤ CC ≤ 68%	63% ≤ CC ≤ 68%
3-day to 1-week	8% ≤ CC ≤ 14%	19% ≤ CC ≤ 36%	44% ≤ CC ≤ 62%	44% ≤ CC ≤ 62%
1-month to 3-month	17% ≤ CC ≤ 24%	23% ≤ CC ≤ 24%	32% ≤ CC ≤ 39%	32% ≤ CC ≤ 39%

Ambitious Offshore Wind

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	14.76	12.63	0.00	0.00	0.02	1.84	7.88	7.07	0.00				
Max. MW	3824	4209	5767	0	0	450	236	2500	5869	0	-2064	1824	-3876	-12

	EnergyPLAN - Ambitious Offshore Wind Scenario - Case study V [14.7 - 12.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	3% ≤ CC ≤ 4%	19% ≤ CC ≤ 43%	98% ≤ CC ≤ 99%	89% ≤ CC ≤ 97%
12-hour to 24-hour	3% ≤ CC ≤ 3%	33% ≤ CC ≤ 40%	89% ≤ CC ≤ 93%	87% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 19%	48% ≤ CC ≤ 53%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Ambitious Onshore Wind

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	16.70	0.00	0.00	0.02	1.84	7.97	7.22	0.00				
Max. MW	3824	3045	7630	0	0	450	236	2500	5869	0	-2020	1860	-3865	-15

	EnergyPLAN - Ambitious Onshore Wind Scenario - Case study V [10.6 - 16.6 - 0 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 4%	17% ≤ CC ≤ 41%	98% ≤ CC ≤ 99%	94% ≤ CC ≤ 97%
12-hour to 24-hour	2% ≤ CC ≤ 3%	31% ≤ CC ≤ 38%	89% ≤ CC ≤ 92%	89% ≤ CC ≤ 92%
3-day to 1-week	6% ≤ CC ≤ 18%	47% ≤ CC ≤ 48%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 29%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Ambitious Wave

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	4.05	0.00	0.01	1.84	7.79	7.10	0.00				
Max. MW	3824	3045	5767	1455	0	450	236	2500	5869	0	-2067	1799	-3854	-12

	EnergyPLAN - Ambitious Wave Scenario - Case study V [10.6 - 12.6 - 4 - 0 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	4% ≤ CC ≤ 5%	19% ≤ CC ≤ 47%	92% ≤ CC ≤ 93%	84% ≤ CC ≤ 89%
12-hour to 24-hour	2% ≤ CC ≤ 4%	34% ≤ CC ≤ 42%	81% ≤ CC ≤ 88%	78% ≤ CC ≤ 88%
3-day to 1-week	12% ≤ CC ≤ 14%	48% ≤ CC ≤ 51%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 30%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Ambitious Solar PV

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	10.68	12.63	0.00	4.08	0.01	1.84	8.03	5.77	0.00				
Max. MW	3824	3045	5767	0	3445	450	236	2500	5869	0	-1787	1903	-3676	-14

	EnergyPLAN - Ambitious Solar PV Scenario - Case study V [10.6 - 12.6 - 0 - 4.1 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 8%	13% ≤ CC ≤ 32%	75% ≤ CC ≤ 82%	71% ≤ CC ≤ 82%
12-hour to 24-hour	4% ≤ CC ≤ 5%	23% ≤ CC ≤ 29%	64% ≤ CC ≤ 67%	63% ≤ CC ≤ 67%
3-day to 1-week	8% ≤ CC ≤ 14%	18% ≤ CC ≤ 35%	44% ≤ CC ≤ 61%	44% ≤ CC ≤ 61%
1-month to 3-month	17% ≤ CC ≤ 23%	22% ≤ CC ≤ 23%	32% ≤ CC ≤ 38%	32% ≤ CC ≤ 38%

Combined RES

	Electricity Demand	Offshore wind	Onshore Wind	Wave	Solar PV	Heat Pumps	Industrial CPH	CHP	PP	PP2	Electricity Exchange	Import	Export	Bottleneck
TWh/y	21.85	4.11	9.58	8.16	5.48	0.01	1.84	7.87	5.41	0.00				
Max. MW	3824	1172	4376	2930	4624	370	236	2500	5869	0	-1682	1877	-3547	-11

	EnergyPLAN - Lund (2006) Scenario - Case study V [4.1 - 9.5 - 8.1 - 5.5 TWh/y]			
	Worst-case Scenario	**Peak demand Scenario**	**Hi-RES Scenario**	**Best-case Scenario**
1-hour to 6-hour	2% ≤ CC ≤ 4%	13% ≤ CC ≤ 35%	73% ≤ CC ≤ 78%	73% ≤ CC ≤ 78%
12-hour to 24-hour	4% ≤ CC ≤ 4%	30% ≤ CC ≤ 49%	57% ≤ CC ≤ 57%	57% ≤ CC ≤ 57%
3-day to 1-week	8% ≤ CC ≤ 13%	23% ≤ CC ≤ 33%	37% ≤ CC ≤ 49%	37% ≤ CC ≤ 49%
1-month to 3-month	16% ≤ CC ≤ 21%	20% ≤ CC ≤ 21%	29% ≤ CC ≤ 34%	29% ≤ CC ≤ 34%

Notes: All calculations relative to this note have been done in the following Excel files:

- *'Output EnergyPLAN.xlsx'*
- *'Cap.Credit Scenarios model - for EnergyPLAN.xlsb'*
- *'Cap. Credit Scenarios model.xlsb'*
- *'Scenarios'*
- *'Date-hour 2013.xlsx'*
- *'Null RES production'*

Annex VIII. Note on the Sensitivity Analyses of Wave and Solar PV Data for year 2013

Date: June, August 2015
Authors: Julia F. Chozas, Consulting Engineer and Brian Vad Mathiesen (AAU).

Goal: Prove the two new data files for year 2013 of wave and solar PV data are representative of Danish available resources.

This note describes a comparative analysis that compares the results of CEESA2030 based on the distribution data files at EnergyPLAN with the results of CEESA2030 based on the two new distribution data for wave and solar PV.

Once the validity of the new files has been proven, the two new files will be included as Distribution Files for the EnergyPLAN model, and as baseline data for the PSO funded project 12134.

Wave data

- Existing files at EnergyPLAN:
  - "*Hour wave 2001*"
  - "*Hour wave 1999*"
  - "*Ireland_wave_power_pelamis_2007*"

- New file, representative of Danish wave power production in year 2013:
  - "*wave power production data DK 2013*"

Files comparison based on the outputs of modelling CEESA 2030 Scenario:

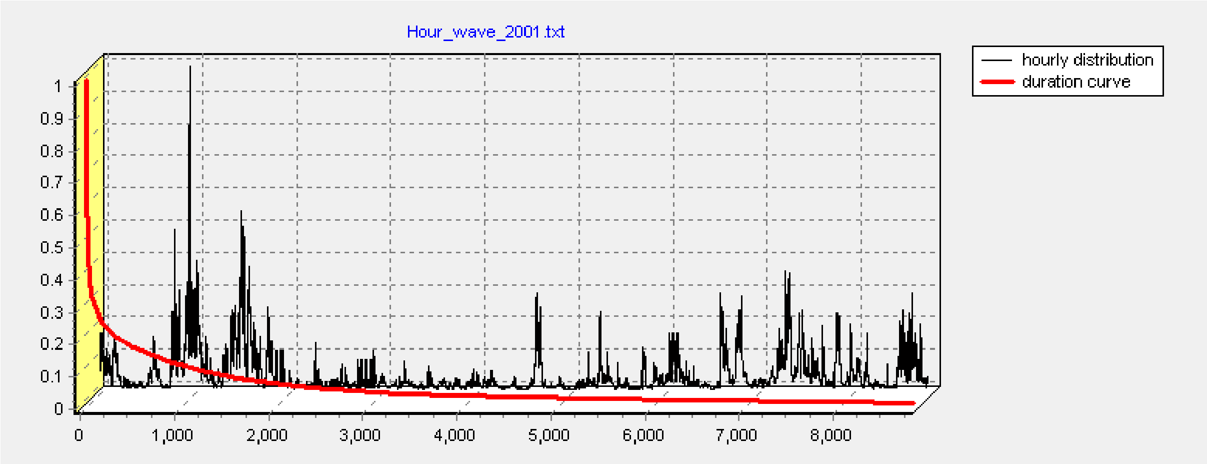
File Name	Comments	Capacity (MW)	Correction factor	Wave power prod. (TWh/y)	Coal (TWh/y)	Oil (TWh/y)	N. Gas (TWh/y)	Biomass (TWh/y)	Renewable (TWh/y)	Total Fuel Consumption (TWh/y)
"Hour wave 1999"		120	0.92	0.32	0.00	43.93	16.54	63.81	37.37	161.66
"Hour wave 2001"	default file in CEESA 2030 Scenario	120	0.93	0.32	0.00	43.93	16.57	63.83	37.38	161.70
"Ireland_wave_power_pelamis_2007"		120	0.45	0.32	0.00	43.93	16.52	63.82	37.38	161.65
"wave power production data DK 2013"		120	0	0.33	0.00	43.93	16.53	63.80	37.39	161.65

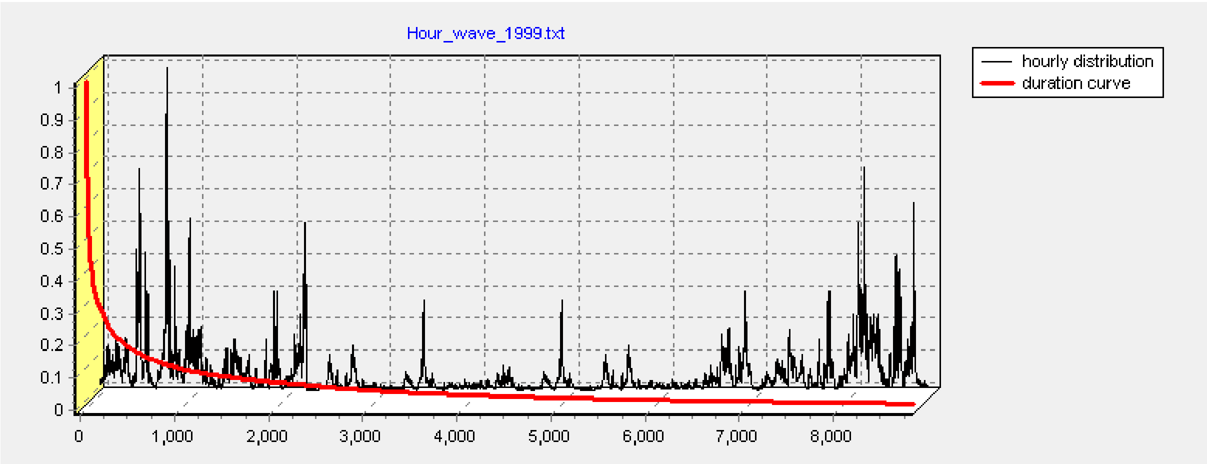
File Name	Excess production CEEP (TWh/y)	Total Costs (MDKK)	Marginal Operation Costs (MDKK)	Total CO2 emission costs (MDKK)	RES share (% of primary energy)	% of electricity	TWh electricity from RES
"Hour wave 1999"	1.80	33801	285	4014	62.6	83.6	33.4
"Hour wave 2001"	1.82	33805	285	4016	61.8	84.4	33.4
"Ireland_wave_power_pelamis_2007"	1.80	33802	284	4013	62.6	83.6	33.4
"wave power production data DK 2013"	1.81	33799	284	4014	62.6	83.6	33.4

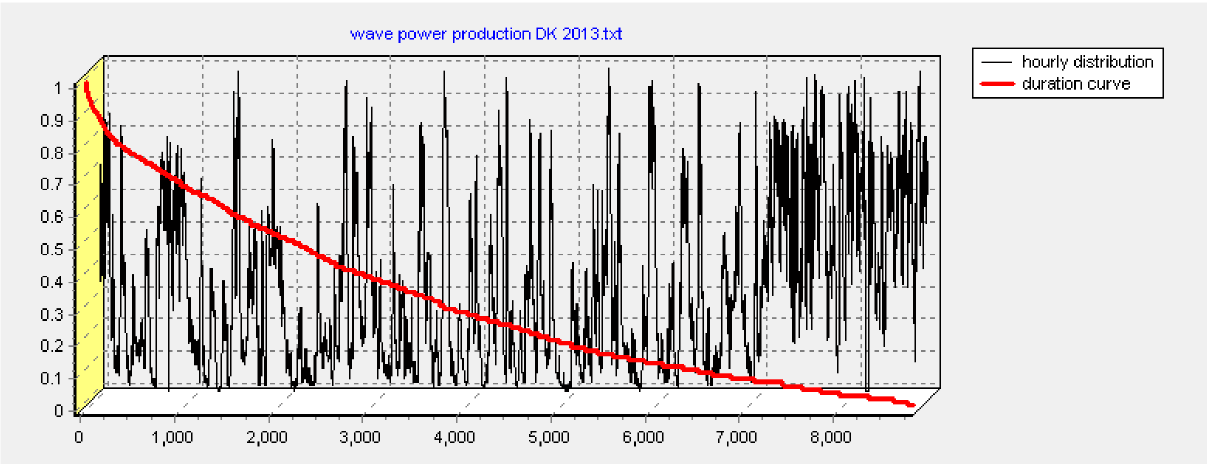
File Name	Comments	Capacity (MW)	Correction factor	Wave power prod. (TWh/y)	Coal (TWh/y)	Oil (TWh/y)	N. Gas (TWh/y)	Biomass (TWh/y)	Renewable (TWh/y)	Total Fuel Consumption (TWh/y)
"Hour wave 1999"		1200	0.9212	3.18	0	43.93	13.76	63.07	40.24	161.00
"Hour wave 2001"	default file in CEESA 20	1200	0.93	3.18	0	43.93	14.16	63.17	40.23	161.49
"Ireland_wave_power_pelamis_2007"		1200	0.447	3.18	0	43.93	13.72	63.12	40.24	161.01
"wave power production data DK 2013"		1200	0	3.34	0	43.93	13.74	62.96	40.40	161.04

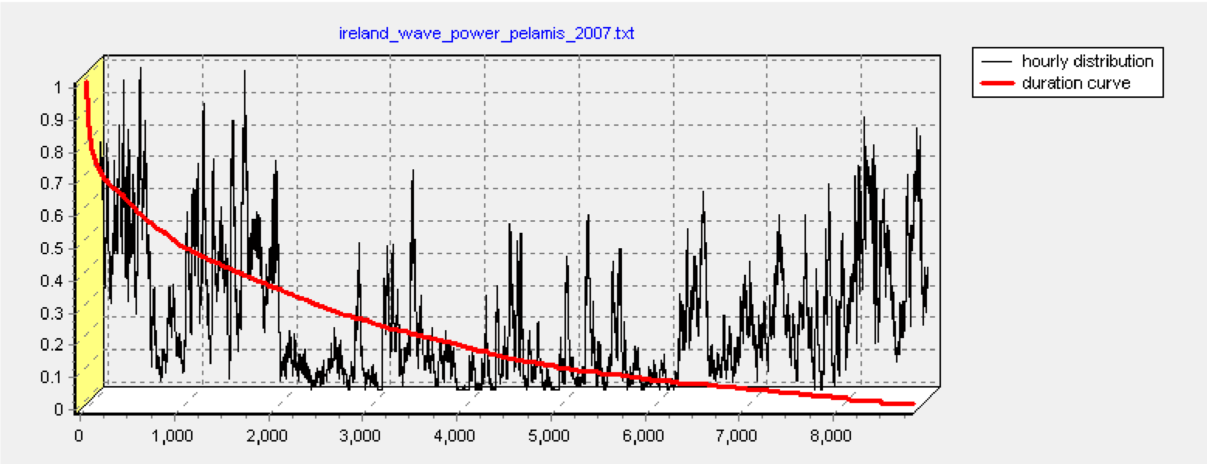
File Name	Excess production CEEP (TWh/y)	Total Costs (MDKK)	Marginal Operation Costs (MDKK)	Total CO2 emission costs (MDKK)
"Hour wave 1999"	2.42	33567	251	3867
"Hour wave 2001"	2.70	33600	256	3889
"Ireland_wave_power_pelamis_2007"	2.40	33575	251	3865
"wave power production data DK 2013"	2.53	33548	251	3866

The hourly distribution and duration curves of the original distribution files (before being multiplied by the correction factor) can be seen below:



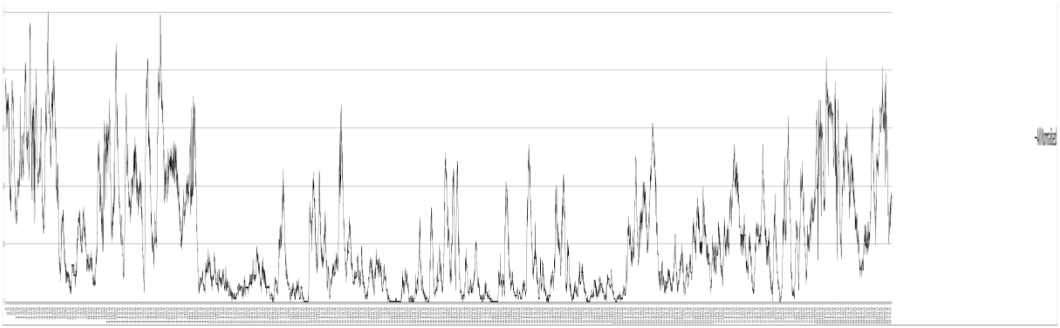




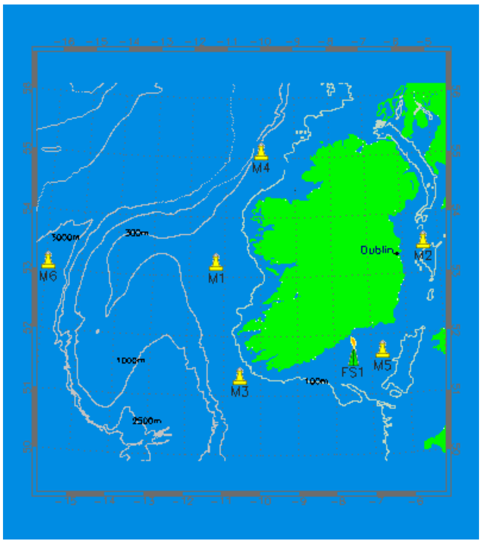


'Ireland_wave_power_pelamis_2007'

This file has been created by David Connolly. More information available at the Excel file 'Scatter Diagrams and Pelamis Power Matrix Comparison'):



➔ Represents the power production of Pelamis in Ireland, as M2, M3, M4 and M5 combined



Solar PV data

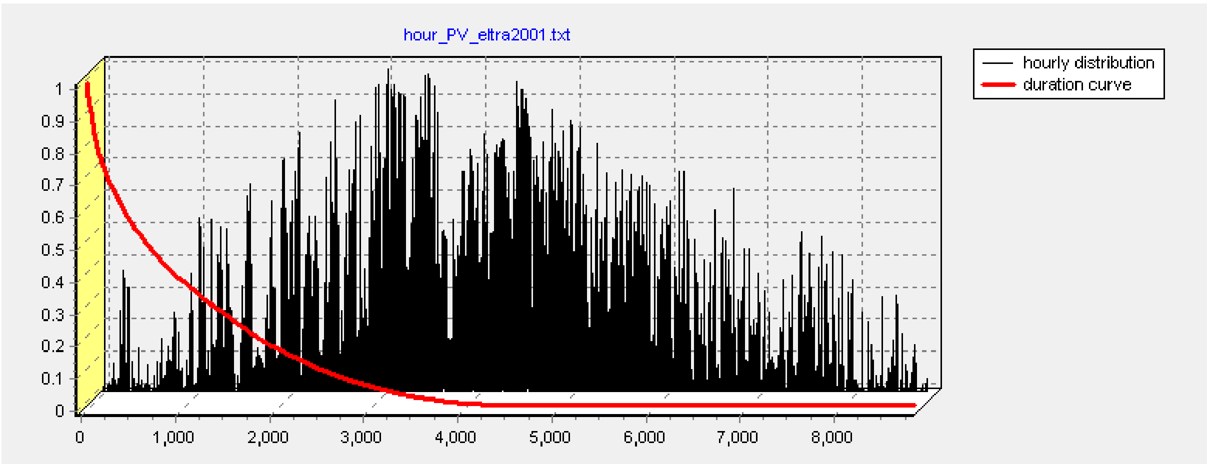
- Existing files at EnergyPLAN:
  - “hour_PV_eltra2001”
  - “hour_PV_eltra2002”
- New files, representative of Danish Solar PV production:
  - “solar PV production - 2013 Dk”
  - “solar PV production - 2014 Dk”

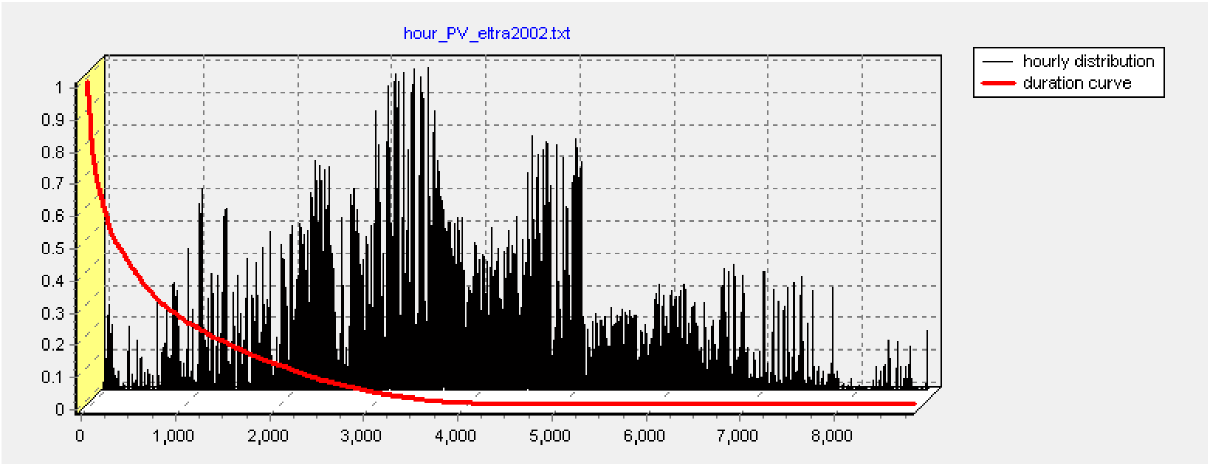
Files comparison based on the outputs of modelling CEESA 2030 Scenario:

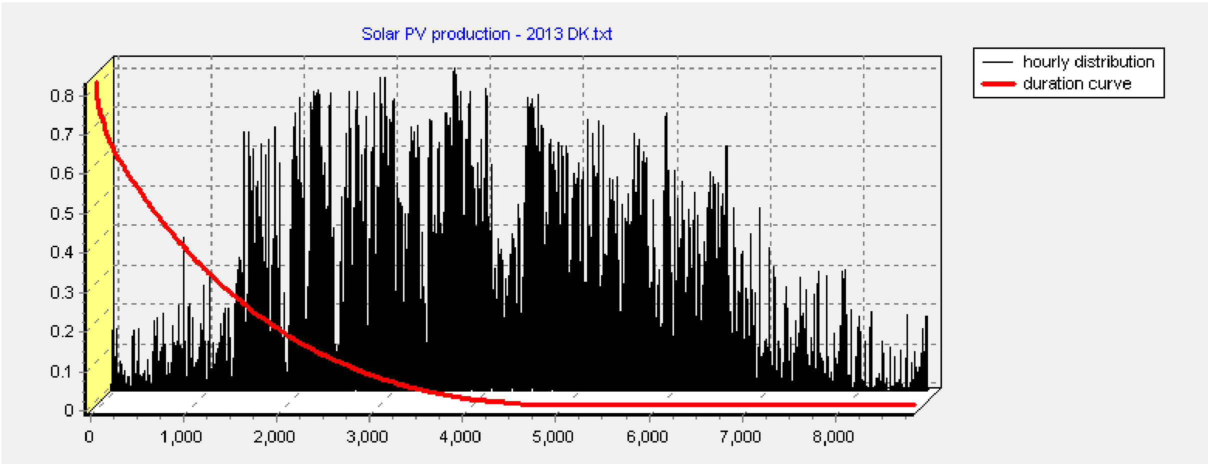
File Name	Comments	Capacity (MW)	Correction factor	Solar PV power prod. (TWh/y)	Coal (TWh/y)	Oil (TWh/y)	N. Gas (TWh/y)	Biomass (TWh/y)	Renewable (TWh/y)
“hour_PV_eltra2001”		3400	0.17	3.76	0.00	43.93	16.44	63.66	37.37
“hour_PV_eltra2002”	default file in CEESA 2030 Scenario	3400	0.505	3.76	0.00	43.93	16.57	63.83	37.38
“solar PV production - 2013 Dk”		3400	0.187	3.76	0.00	43.93	16.47	63.75	37.37
“solar PV production - 2014 Dk”		3400	0.212	3.76	0.00	43.93	16.52	63.70	37.38

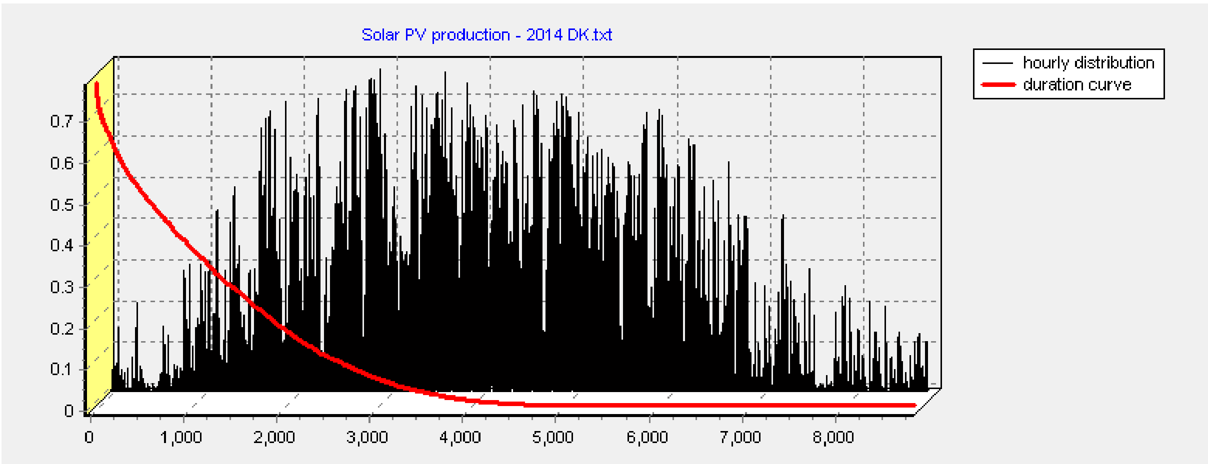
File Name	Total Costs (MDKK)	Marginal Operation Costs (MDKK)	Total CO2 emission costs (MDKK)
“hour_PV_eltra2001”	33771	283	4009
“hour_PV_eltra2002”	33805	285	4016
“solar PV production - 2013 Dk”	33789	284	4011
“solar PV production - 2014 Dk”	33782	284	4013

The hourly distribution and duration curves of the original distribution files (before being multiplied by the correction factor) can be seen below:









Conclusions:

All compared files representing wave power, and all files representing solar PV, lead to approximately the same results – provided the correction factor is changed in order to provide the same power production. Therefore, it can be concluded that the two data distribution files developed for year 2013 are representative of the Danish conditions

Annex IX. Paper presented and published at the 14th Wind Integration Workshop Proceedings, Brussels

Capacity Credit and System Adequacy

The Case of Wind, Wave and Solar PV in the Danish System

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Abstract— **This paper addresses the question of how variable renewable energy production can be included in the planning of the electricity system as a substitute for conventional electricity generation, and with what weight. In order to answer this question, the study investigates the contribution of variable renewable energies to security of supply and system adequacy in Denmark. The study is based on hourly 2013 data from offshore wind, onshore wind, wave and solar PV power production. The analysis is done over a year based on hourly values and based on a historical year. Provided that the capacity credit is the amount of power variable renewables can reliably be expected to produce at the times when demand for electricity is highest, the study focuses on the capacity credit of future Danish scenarios including high penetrations of offshore wind, onshore wind, wave and solar PV. The results of this project can ultimately lead towards the improvement of existing rules and methods in system planning and the development of integrated energy systems where the electricity, heating and transport sectors are merged.**

Keywords- Capacity credit; Denmark; security of supply; system adequacy; system planning; renewable energy; offshore and onshore wind energy; wave energy; solar photovoltaic.

I. Introduction

EU energy policies and those of its member states focus on three main objectives: increasing the use of renewable energy, enhancing security of supply and reducing climate impact. This is also the case of Denmark, which has set ambitious goals in the energy sector. By 2035, it aims to be independent of fossil fuels in the heat and electricity sector. In order to achieve 2035 goals, wind generation is meant to increase significantly.

The integration of variable renewable energies (RE) in traditional energy systems poses new challenges. Whilst variable renewable energies are not dispatchable and vary by the whim of nature, the electricity system has to maintain the balance of supply and demand at each hour of operation.

This study addresses the question of how traditional (i.e. wind) and new (i.e. solar photovoltaic (PV) and wave) variable renewable energies can contribute to security of supply. Denmark is the reference system of this analysis, and the capacity credit is the parameter of focus.

The Danish electricity system is characterized by a high percentage of wind generation (in the first half of 2015 it produced about 40% of the electricity demand), high percentage of CHP (combined heat and power) plants, and strong interconnections to surrounding countries. The plan for future years (year 2020 and beyond) is having a system with more energy savings, higher penetrations of wind, small amounts of solar PV and no wave energy; stronger international connections; no diesel or coal power plants, and very low capacity of gas turbines [1].

II. Security of Supply, System Adequacy and Long-term System Planning

System planning is the process that assures security of supply and system adequacy, i.e. the ability for the system to meet peak demand even under the most extreme condition. Traditional long-term system planning and system adequacy analyses elaborated by Energinet.dk (i.e. the Danish TSO or Transmission System Operator) under the recommendations of the ENTSO-E (European Network of Transmission System Operators for Electricity), are carried out based upon the fact that conventional power plants have a positive capacity credit, i.e. can contribute to system's security of supply. On the other hand, the traditional general assumption in adequacy forecasts is that variable renewable generation cannot contribute to system adequacy.

Basically, system adequacy forecasts evaluate the ability of generation units to operate when most needed by the system; this is, in hours of peak demands. Traditionally, this analysis has been based on the capacity credit parameter, which is calculated on a yearly basis and evaluates the amount of power variable renewables can reliably be expected to produce at the times when demand for electricity is highest. Accordingly, the study calculates the capacity credit of different renewable energy portfolios representative of future Danish system scenarios.

Capacity Credit

The Capacity Credit (CC), also known as capacity value, measures the contribution of a power plant to reliably meet demand [2]. It is measured either in terms of physical capacity (in MW) or the fraction of a power plant rated capacity (%). The term also refers to the conventional capacity that a variable generator can replace without compromising system reliability [3]. For example, a plant with 150 MW rated power and a capacity value of 50% could reduce the need for conventional capacity by 75 MW.

Results from regional system adequacy forecasts indicate that there is not yet a national TSO standard for the determination of RE's capacity credit [4], and different methodologies for its calculation are recommended [2, 3, 5, 6].

In the study context, it is calculated as the amount of power variable renewable energies can reliably be expected to produce at times of peak demand [2, 7].

III. Quantitative Assessment

This section assesses the contribution that variable renewable energies can have to security of supply. The study is done by computing the capacity credit of a RE mix as the aggregated output of the RE mix in hours when demand for electricity is highest [2, 7]. Results are expressed as the fraction of the rated capacity of RE mix that adds to system reliability. The analysis is done over a year based on hourly values.

Reference system

Denmark is the reference system and year 2013 is the reference year. These have allowed having real hourly renewable energy sources (RES) production data as input of the study. 2013 data have also served for calculating average annual Danish Capacity factors (Cf) of offshore wind, onshore wind, wave and solar PV technologies; these being 40%, 25%, 32% and 11%, respectively.

RES hourly distribution data files

Renewable energy sources included in the analyses are offshore wind, onshore wind, wave and solar photovoltaic (they are always referred to in this same order). Hour by hour distributions of the different RES have been based on actual measurements whenever possible. For offshore wind, onshore wind and solar PV this has been possible. Data files are based on real hourly measured productions during year 2013, and they do take into account the spatial distribution of RES at a whole Danish level.

Such data do not exist for commercial wave energy farms. Consequently, wave production data have been generated from half-hourly wave measurements throughout year 2013 in two sites in the Danish North Sea, Hanstholm and Horn Rev 3. Having H_{m0} and T_{02} as input values, the transfer function has been Wavestar Wave Energy Converter (WEC) power matrix. Output values are hourly power production of Wavestar at the two selected locations. Based on these power productions, a distribution file representative of wave production data in the Danish North Sea has been created. Thus, the data file takes into account the spatial distribution of wave power along the Danish west coast, but it is not representative of the wave potential further offshore in the Danish North Sea.

Study periods

As of interest to national TSOs *and* the ENTSO-E, this study examines how well the aggregated production of variable RES aligns with periods during which the system faces a high risk of an outage, i.e. periods of peak demand. Additionally, it is also of interest to investigate how RE production aligns with a subset of periods where electricity demand is low or RE production is high. Accordingly, the study focuses on four different periods (named as follows) characterized by:

Worst periods: maximum Electricity demand and minimum RE production.

Peak-demand periods: maximum electricity demand

Hi-RES periods: maximum RE production.

Best periods: minimum demand and maximum RE production.

Time spans

Nine different time spans are considered in the analysis of each study period. They are intended to represent the contribution of RES on an hourly basis, intra-day basis, intra-week basis, weekly basis, monthly basis and season basis. Time spans selected for the study are: 1-hour, 3-hour, 6-hour, 12-hour, 1-day, 3-day, 1-week, 1-month and 3-month. For every time span the average value for the indicated consecutive hours is measured (for example, the 3-hour value is calculated as the average value of 3 consecutive hours). Representative time spans do not necessarily need to be consecutive; this is, from the same day or hour as the immediately lower or higher time-span. The selected time span represents the consecutive averaged hour/hours in a year where the case of study occurs.

Definition of scenarios

For the purpose of the capacity credit analysis five future scenarios with different mixes of RES are studied. Year 2030 is the study year and scenarios are based on CEESA2030 Scenario, which is constituted by the following features: total RE production of 27.38 TWh/y and total electricity consumption of 41.38 TWh/y, of which 21.85 TWh/y corresponds to classical electricity demand, 3.93 TWh/y to flexible demand, 4.59 TWh/y to the electric demand in the transport sector (i.e. electric vehicles), 3.66 TWh/y to consumption of industrial heat pumps, and 7.01 TWh/y to electrolysers and households' heat pumps and electric boilers. CEESA2030 Scenario is described in [8] and is based on the smart energy design concept described in [9-11].

Scenarios are built based year 2013 data and on CEESA2030 Scenario. Scenarios are designed as follows: annual total power production from RES is kept constant at 27.3 TWh/y (same value as in CEESA2030); production from offshore and onshore wind is kept equal or higher than 10.7 and 12.6 TWh/y, respectively, as defined by CEESA2030; and full-load hours (or capacity factors) of each technology type are defined by 2013 values. Once productions of each RES are fixed and full-load hours are known, the installed capacity of each RES is calculated. Further information on how scenarios are built can be found in [12, 13].

The five scenarios of the analysis are detailed below. Some of them can indeed be compared to current or planned future Danish scenarios. The *Ambitious Onshore wind scenario* can be compared to the RE mix in year 2013 in Denmark; the *Ambitious Offshore Wind Scenario* is representative of ENS Wind 2035 scenario [1], and *Ambitious Solar PV Scenario* of CEESA2030 Scenario [8].

1) Ambitious Offshore Wind Scenario: here offshore wind power production is increased to a maximum value, onshore wind power production is kept at CEESA2030 values, and there is no production from wave or solar PV.

2) Ambitious Onshore Wind Scenario: here offshore wind power production is kept at CEESA2030 values, onshore wind production is increased to a maximum value, and there is no production from wave or solar PV.

3) Ambitious Wave Scenario: here offshore and onshore wind productions are kept at CEESA2030 values, wave production is increased to 4 TWh/y (15% of total RES production), and there is no production from solar PV.

4) Ambitious Solar PV Scenario: here offshore and onshore wind productions are kept at CEESA2030 values, there is no production from wave energy, and solar PV production is increased to 4 TWh/y (15% of total RES production).

5) Combined RES Scenario: this scenario is defined based on the findings of [13], which to the authors knowledge, is the first Danish study looking into optimal combinations of the four RES of the project with high RE system penetration. The paper suggests an optimal mix of RES for Denmark when production from RES is above 80% of total production. Lund's analysis is done from a technical point view, where the optimisation parameter is the minimum excess production. In this scenario offshore wind produces 15% of the total RES production, onshore wind 35%, wave 30% and solar PV 20%.

System approach

Two system approaches to the capacity credit calculations are implemented: an electricity-only system approach and an integrated energy system approach. The two approaches consider much differentiated systems. The electricity-only system's approach looks into the electricity sector as an isolated energy system, whereas an integrated energy systems' approach is founded on a holistic system perspective that integrates the consumption in all energy sectors: transport, heat, industry and electricity. The first approach responds to the traditional analysis, where the focus is put only on the classical electricity consumption. Besides classical electricity consumption, the second approach also takes into account flexible electricity consumption, electricity demand in the transport sector (i.e. electric vehicles), and consumption of industrial and household heat pumps, of electrolysers and households' electric boilers.

Electricity consumption hourly distribution data

According to the description above two different electricity consumption patterns are utilised in the analysis: one representative of a classical electricity demand and another one illustrative of the electricity consumption in an integrated energy system. The first set of data has been directly obtained from [14]; it takes into account the spatial distribution of the electricity consumption at a whole Danish level and it only contains the classical electricity consumption projected for year 2035. The dataset representative of an integrated electricity consumption pattern is calculated as an output parameter of the EnergyPLAN model, as described below.

Model

Two models are used for the analyses, an in-house model developed for the project and EnergyPLAN Model. The in-house model allows to calculating the individual and aggregated capacity credit of a given RE mix in a given system for all the time spans of the analysis. Input data are hourly RE production and hourly electricity demand.

EnergyPLAN Model [15] is an advanced energy system's modelling tool for energy systems' analysis. It has been developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark. As a result, it is now a very complex tool which considers a wide variety of technologies, costs and regulations strategies for an energy system that includes heat and electricity supplies as well as the transport and industrial sectors. It is a deterministic input/output tool and general inputs are demands, renewable energy sources, energy station capacities, costs and a number of different regulation strategies for import/export and excess electricity production. Also, EnergyPLAN simulates the energy system on an hourly basis over one year. The hourly time-step is essential to ensure that intermittent renewable energy is capable of reliably meeting the demands for electricity, heat and transport. In the analysis a technical simulation strategy that balances both heat and electricity demands has been used.

IV. RESULTS AND DISCUSSION

This section presents the aggregated capacity credit of different mixes of RES for each of the four study periods, for each time span and calculated from two different approaches. A large number of results have been derived for this analysis [12, 16] but due to space constraints only the most illustrative ones are presented here.

First, results derived from an electricity-only system approach are presented. Then, these are compared with results based on an integrated energy system approach.

Electricity-only system approach

Table 1 shows the capacity credit in five scenarios with different mixes of RES (as indicated by the numbers in brackets, which show the annual production of offshore wind, onshore wind, wave and solar PV, respectively) for four study periods and for various time spans. Capacity credit results can be read as the percentage of the total RE installed capacity available in that study period and at that time span.

Integrated energy system approach

Table 2 show the capacity credit in five scenarios with different mixes of RES (as indicated by the numbers in brackets, which show the annual production of offshore wind, onshore wind, wave and solar PV, respectively) for four study periods and for various time spans. Capacity credit results can be read as the percentage of the total RE installed capacity available in that period and at that time span. Results are derived with EnergyPLAN energy system's model using a technical strategy that optimizes, i.e. minimizes, fuel consumption, and adjusts demands according to what is possible with the installed technologies.

TABLE I. CAPACITY CREDIT OF RES EXPRESSED AS THE PERCENTAGE OF THE TOTAL RE INSTALLED CAPACITY, CALCULATED FROM AN ELECTRICITY-ONLY SYSTEM APPROACH. RESULTS FOR DIFFERENT PERIODS AND TIME SPANS ARE SHOWN. NUMBERS IN BRACKETS SHOW ANNUAL PRODUCTION OF OFFSHORE WIND, ONSHORE WIND, WAVE AND SOLAR PV, RESPECTIVELY, IN THE CHOSEN SCENARIO. FIVE SCENARIOS ARE SHOWN.

Electricity-only System Approach - Ambitious Offshore Wind Scenario [14.8 - 12.5 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	1% ≤ CC ≤ 3%	9% ≤ CC ≤ 30%	98% ≤ CC ≤ 99%	90% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 4%	17% ≤ CC ≤ 27%	89% ≤ CC ≤ 93%	82% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 16%	15% ≤ CC ≤ 29%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 31%	31% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Electricity-only System Approach - Ambitious Onshore Wind Scenario [10.7 - 16.6 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 28%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 94%
12-hour to 24-hour	2% ≤ CC ≤ 3%	15% ≤ CC ≤ 25%	89% ≤ CC ≤ 92%	81% ≤ CC ≤ 85%
3-day to 1-week	6% ≤ CC ≤ 15%	13% ≤ CC ≤ 27%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 21%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Electricity-only System Approach - Ambitious Wave Scenario [10.7 - 12.5 - 4 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	3% ≤ CC ≤ 3%	8% ≤ CC ≤ 30%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 4%	16% ≤ CC ≤ 27%	81% ≤ CC ≤ 87%	78% ≤ CC ≤ 82%
3-day to 1-week	7% ≤ CC ≤ 16%	14% ≤ CC ≤ 28%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Electricity-only System Approach - Ambitious Solar PV Scenario [10.7 - 12.5 - 0 - 4.2 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 19%	71% ≤ CC ≤ 77%	67% ≤ CC ≤ 77%
12-hour to 24-hour	2% ≤ CC ≤ 3%	11% ≤ CC ≤ 18%	60% ≤ CC ≤ 63%	56% ≤ CC ≤ 59%
3-day to 1-week	5% ≤ CC ≤ 12%	10% ≤ CC ≤ 20%	41% ≤ CC ≤ 57%	41% ≤ CC ≤ 57%
1-month to 3-month	16% ≤ CC ≤ 22%	21% ≤ CC ≤ 22%	30% ≤ CC ≤ 36%	30% ≤ CC ≤ 36%

Electricity-only System Approach - Combined RES Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 4%	7% ≤ CC ≤ 18%	68% ≤ CC ≤ 73%	68% ≤ CC ≤ 73%
12-hour to 24-hour	3% ≤ CC ≤ 3%	10% ≤ CC ≤ 16%	53% ≤ CC ≤ 53%	53% ≤ CC ≤ 53%
3-day to 1-week	5% ≤ CC ≤ 11%	8% ≤ CC ≤ 17%	34% ≤ CC ≤ 46%	34% ≤ CC ≤ 46%
1-month to 3-month	15% ≤ CC ≤ 20%	19% ≤ CC ≤ 20%	27% ≤ CC ≤ 31%	27% ≤ CC ≤ 31%

Influence on the approach to the CC_{REmix}

It is of much interest to investigate if the capacity credit of the renewable energy portfolio (CC_{REmix}) of focus changes when modelling it within an electricity-only system or in an integrated energy system.

The biggest difference is in the capacity credit of *peak-demand periods*. Particularly, for the capacity credits within the intra-day time scale, i.e. in the 1-hour to 24-hour interval. When an integrated energy system is considered the CC_{REmix} increases, reaching almost the capacity credits of the *hi-RES periods*. The raise is highest for the smallest time span (i.e. 1-hour) and it is less pronounce as the time span increases. However, CC_{REmix} improves only slightly for the worst periods in the 1-hour to 24-hour time spans. This can be explained by the fact that in *worst periods* RES production is minimum, and therefore there is no opportunity in the system to transfer the electricity production from RES to other hours. In an integrated system it will be possible to (and indeed EnergyPLAN model does so) shift peak-demand hours to hours where RES production is high, and the direct results of that approach can be seen here. By implementing an integrated energy system approach, CC_{REmix} in *peak-demand* periods increases significantly and it almost reaches the values achieved in *hi-RES periods* and *best periods*.

For daily, weekly and monthly time spans, CC_{REmix} does not change significantly if in an electricity-only system or an integrated energy system. This can be explained by the fact that integrated energy systems have a smoothing effect with regards to the integration of RES on the intra-day timescale.

TABLE II. CAPACITY CREDIT OF RES EXPRESSED AS THE PERCENTAGE OF THE TOTAL RE INSTALLED CAPACITY, CALCULATED FROM AN INTEGRATED ENERGY SYSTEM APPROACH. RESULTS FOR DIFFERENT PERIODS AND TIME SPANS ARE SHOWN. NUMBERS IN BRACKETS SHOW ANNUAL PRODUCTION OF OFFSHORE WIND, ONSHORE WIND, WAVE AND SOLAR PV , RESPECTIVELY, IN THE CHOSEN SCENARIO. FIVE SCENARIOS ARE SHOWN.

Integrated Energy System Approach - Ambitious Offshore Wind Scenario [14.8 - 12.5 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	4% ≤ CC ≤ 6%	77% ≤ CC ≤ 91%	98% ≤ CC ≤ 99%	90% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 3%	40% ≤ CC ≤ 59%	89% ≤ CC ≤ 93%	87% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 22%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Integrated Energy System Approach - Ambitious Onshore Wind Scenario [10.7 - 16.6 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	3% ≤ CC ≤ 5%	75% ≤ CC ≤ 90%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 94%
12-hour to 24-hour	2% ≤ CC ≤ 3%	38% ≤ CC ≤ 55%	89% ≤ CC ≤ 92%	86% ≤ CC ≤ 92%
3-day to 1-week	6% ≤ CC ≤ 18%	18% ≤ CC ≤ 21%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 29%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Integrated Energy System Approach - Ambitious Wave Scenario [10.7 - 12.5 - 4 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	3% ≤ CC ≤ 5%	75% ≤ CC ≤ 79%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 5%	42% ≤ CC ≤ 70%	81% ≤ CC ≤ 88%	78% ≤ CC ≤ 88%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 24%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 30%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Integrated Energy System Approach - Ambitious Solar PV Scenario [10.7 - 12.5 - 0 - 4.2 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 7%	60% ≤ CC ≤ 71%	75% ≤ CC ≤ 82%	71% ≤ CC ≤ 82%
12-hour to 24-hour	1% ≤ CC ≤ 4%	49% ≤ CC ≤ 52%	64% ≤ CC ≤ 67%	59% ≤ CC ≤ 63%
3-day to 1-week	8% ≤ CC ≤ 14%	14% ≤ CC ≤ 16%	44% ≤ CC ≤ 61%	44% ≤ CC ≤ 61%
1-month to 3-month	17% ≤ CC ≤ 23%	22% ≤ CC ≤ 23%	32% ≤ CC ≤ 38%	32% ≤ CC ≤ 38%

Integrated Energy System Approach - Combined RES Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 7%	55% ≤ CC ≤ 65%	73% ≤ CC ≤ 78%	73% ≤ CC ≤ 78%
12-hour to 24-hour	3% ≤ CC ≤ 6%	30% ≤ CC ≤ 48%	57% ≤ CC ≤ 57%	57% ≤ CC ≤ 57%
3-day to 1-week	8% ≤ CC ≤ 13%	18% ≤ CC ≤ 33%	37% ≤ CC ≤ 49%	32% ≤ CC ≤ 49%
1-month to 3-month	16% ≤ CC ≤ 21%	20% ≤ CC ≤ 21%	29% ≤ CC ≤ 34%	24% ≤ CC ≤ 26%

In the scenarios where there is solar PV installed, the CC_{REmix} in all time spans increases if an integrated energy system approach is used.

The comparison in numbers among CC values achieved with an electricity-only system approach and an integrated energy system approach are the following:

- Minimum, maximum and average CC_{REmix} values depend on the periods considered: worst periods, peak-demand periods, hi-RES periods or best periods.

- Generally, CC_{REmix} values are of the same range and follow the same trends for every scenario of the analysis.

- As a general trend $CC_{Offshore\ wind} > CC_{Wave} > CC_{Onshore\ wind} > CC_{Solar\ PV}$; and CC_{REmix} is proportional to this relationship, it increases or decreases accordingly to the contribution of each RES in the mix. For example, increasing offshore wind or wave in a scenario increases CC_{REmix} more than if solar PV was added to that scenario, as can be seen by comparing the scenarios *Ambitious Offshore Wind* or *Ambitious Wave* with the *Ambitious Solar PV* or *Combined RES*.

- In an electricity-only system the minimum aggregated contribution that RES can have in worst periods is 1% to 3% and for the 1-hour time span. Also in worst periods but for 3-month time spans, CC_{REmix} increases to 20% - 31%. These numbers increase slightly in an integrated energy system, rising to 2% to 4% for the 1-hour time span.

- *Peak-demand periods* do not coincide with minimum CC values. In an electricity-only system CC_{REmix} during peak-demand periods range from 7-8% for the 1-hour interval to 16%-27% in the 24-hour interval. Numbers do change significantly in an integrated energy system and increase to 55%-77% for the 1-hour interval and to 48%-70% in the 24-hour interval.

- Maximum contributions that RES can have happen on *best periods* and for the 1-hour interval. Values are 70-80-99% depending on the RE mix. As it can be expected, values lower a bit in an integrated energy system approach.

- The average contribution that can be expected from RES, i.e. overall average CC_{REmix}, can be suggested to be the monthly average. It varies in the range 15%-45%, depending on the scenario. This is true in both an electricity-only and in an integrated energy system. The average CC_{REmix} is close to the average capacity factor of the RE mix (Cf_{REmix}) during the period of consideration. This is in line with [3], who state that the CC_{REmix} can at most equal Cf_{REmix}.

CONCLUSIONS

The methodology traditionally used by TSOs, the ENTSO-E and the IEA to calculate the Capacity Credit of RES does not seem suitable when variable RES are part of the electricity generation mix. Accordingly, an approach has been developed that looks into the Capacity Credit of a RE mix for different time spans (intraday, intraweek, intermonth and seasonally) and key time periods during a year (worst, peak-demand, high RES and best periods), and not only during the 10^{th}-100^{th} highest consumption hours of the year.

The following recommendations might be taken as part of a new methodology on how to evaluate the contribution that RES can have in system adequacy, i.e. on the evaluation of the parameter CC_{REmix}. These recommendations aim to go beyond the traditional approach used in adequacy forecasts:

- Investigate RE production at key time periods during a year, instead of only calculating RE production during a given number of highest consumption hours per year.

- Examine RE production throughout different time spans taking into account intra-daily and daily variations in consumption. This is especially important as changes in demand patterns are expected and peak demand hours might be shifted to other hours in the day where demand is lower or RE production is higher.

- Evaluate RE production in an integrated energy system and not only from a classical electricity consumption perspective. As decisions in 20-30 year time are happening now, it is important that this decision processes take into account changes in demand patterns, as well as changes on how the electricity and the other energy sectors (transport, heat and industry) will interact. This is addressed in this study by implementing an electricity-only system approach and an integrated energy system; and differences of using one and the other have been shown.

- Accordingly, integrated energy systems need to be developed, where components from all sectors will be able to contribute to the system electrical balance and hence increase the capacity credit of RE technologies [17].

- Two very different periods should be distinguished: *worst periods* and *peak-demand periods*. Whereas on the former RE production is minimal and peak demand is maximal, the latter only takes into account periods of peak demand. Therefore, worst periods are interesting to study how the whole system (with minimum amounts of RES) can meet security of supply, and peak-demand periods to study what can the contribution of RES be in periods when electricity consumption is highest.

- Energinet.dk [18] and the Danish Energy Authority [1] project an improvement of wind and wave harnessing technologies; and as such, their Cf are expected to increase significantly. These improvements provide a different scenario as the one analyzed in this paper, and this is especially true for wave technologies, which in some cases are expected to have Cf higher than for offshore wind. If this proves true, the picture of the aggregated capacity credit of RE can change positively. Overall, technology developments will come along with higher contribution of RE to system adequacy.

Overall, the contribution that can be expected from RES averaged over a month is in the range 15%- 45%, depending on the scenario.

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II. REFERENCES

[1] Energistyrelsen. “Energiscenarier frem mod 2020, 2035 og 2050 (Energy Scenarios for 2020, 2035 and 2050)”, Energistyrelsen, 2014.
[2] NREL. “Using wind and solar to reliably meet electricity demand” National Renewable Energy Laboratory, NREL, 2015.
[3] R. Gross et al., "Renewables and the grid: understanding intermittency". Energy 160. Proceedings of the Institution of Civil Engineers, 2007, pp. 31-41.
[4] EWEA. Wind Energy The Facts. EWEA, 2009.
[5] G. Giebel, ‘Wind power has a capacity credit – A catalogue of 50+ supporting studies’ Wind Eng E Journal, 2005.
[6] OECD/IEA, “World Energy Model - Modelling the capacity credit of renewable energy sources”, OECD/IEA, 2011.
[7] OECD/IEA. “World Energy Outlook”. OECD/IEA, 2011.
[8] Lund, H, Hvelplund, F, Mathiesen, BV, Østergaard, PA, et al. “Coherent Energy and Environmental System Analysis”. Aalborg University, Department of Development and Planning, Technology, Environment and Society, 2011.
[9] Mathiesen, B. V., Lund, H., Karlsson, K, “100% Renewable energy systems, climate mitigation and economic growth”. Applied Energy, 88(2), 488-501, 2011.
[10] Lund, H., Andersen, A. N., Østergaard, P. A., Mathiesen, B. V., Connolly, D., “From electricity smart grids to smart energy systems: A market operation based approach and understanding”. Energy, 42(1), 96-102., 2012.
[11] Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P. A., Möller, B, et al. “Smart Energy Systems for coherent 100% renewable energy and transport solutions”. Applied Energy, 145, 139–154, 2015.
[12] Fernandez-Chozas, J. and Mathiesen, B.V., “Capacity Credit and Security of Supply: the Case of Renewable Energies in Denmark” Book of Abstracts: 10th Conference on Sustainable Development of Energy, Water and Environment Systems, 2015.
[13] Fernandez-Chozas, J., “Capacity Credit of Wave and Solar PV” Final Project Report. Energinet.dk, PSO-ForskVE-12134, 2015.
[14] Lund, H. “Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply” Renewable Energy, 2006, pp. 503-515.
[15] Energinet.dk. Input from the Meeting at Energinet.dk with the System Analysis Dept. and Operation's Dept. (8/9/2014). 2014.
[16] EnergyPLAN. “EnergyPLAN: Advanced Energy System Analysis Computer Model”. Aalborg University, www.energyplan.eu, 2015.
[17] Mathiesen, B.V., Lund, H. 2009, “Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources” IET Renewable Power Generation, 3(2), 190-204.
[18] Energinet.dk. "Energi 2050 – Vindsporet". Dok. 6357/11, 2011

Annex X. Paper presented and published at the 10th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES Conference), Dubrovnik

Capacity Credit and Security of Supply: the Case of Renewable Energies in Denmark

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ABSTRACT

This paper addresses the question of how renewable energies can contribute to security of supply. In order to analyse this subject, the paper has two differentiated parts. In the first part, the concept of security of supply is reviewed. This provides the baseline to understand how current electricity systems are planned, and how renewable energies fit in these systems. The second part of the article assesses the actual contribution that variable renewable energies can make to security of supply, firstly from a qualitative point of view and secondly in measurable terms. The study is based on historical hourly 2013 data from offshore wind, onshore wind, wave and solar PV power production and is done over a year.

Provided that the capacity credit is the amount of power variable renewables can reliably be expected to produce at the times when demand for electricity is highest, the study focuses on the capacity credit of various future 2030 Danish scenarios including high penetrations of offshore wind, onshore wind, wave and solar PV.

The results of this project can ultimately lead towards the improvement of existing rules and methods in system planning and the development of integrated energy systems where the electricity, heating and transport sectors are merged.

KEYWORDS

Capacity credit; security of supply; system adequacy; system planning; Denmark; renewable energy; offshore and onshore wind energy; wave energy; solar photovoltaic.

INTRODUCTION

EU energy policies and those of its member states focus on three main objectives: increasing the use of renewable energy, enhancing security of supply and reducing climate impact. This is also the case of Denmark, which has set ambitious goals in the energy sector. By 2035, it aims to be independent of fossil fuels in the heat and electricity sector. In order to achieve 2035 goals, wind generation is meant to increase significantly.

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The integration of variable renewable energies in traditional energy systems poses new challenges. Whilst variable renewable energy sources (RES) are not dispatchable and vary by the whim of nature, the electricity system has to maintain the balance of supply and demand at each hour of operation.

The aim of this study is to evaluate the contribution that traditional, i.e. wind, and new, i.e. solar photovoltaic (PV) and wave, variable renewable energy (RE) generation can have to security of supply of a given electricity system. Denmark is the reference system of this analysis, and the capacity credit is the parameter of focus. Today wind power plays an important role to the Danish electricity system; it produces up to 40% of the total annual electricity demand. Solar photovoltaic (solar PV) is becoming more and more relevant in the Danish system, and generation from wave energy converters is also expected to happen in future years.

Overall, this study addresses the question of how renewable energies can contribute to security of supply. In order to analyse this subject, the paper has two differentiated parts. In the first part, the concept of security of supply is reviewed. This provides the baseline to understand how current electricity systems are planned, and how renewable energies fit in these systems. The second part of the article assesses the actual contribution that variable renewable energies can make to security of supply, firstly from a qualitative point of view and secondly in measurable terms.

SECURITY OF SUPPLY, SYSTEM ADEQUACY AND LONG-TERM SYSTEM PLANNING

This section reviews the concept of security of supply by addressing the following questions: What are the traditional and current approaches to assess long-term security of supply, which parameters are relevant in this assessment, how security of supply is related to system planning and which time scales appear in system planning. The purpose of this section is to provide the framework of discussion for the qualitative and quantitative assessments to be presented in the second part of the paper.

System Planning and System Operation

Figure 1 shows the structure and time-intervals of electricity systems. In the timeline the different concepts of system operation, operational planning and system planning are described. The diagram represents these concepts and how they are interrelated in time. These parameters are related to the present project and the capacity credit discussion.

When analysing electricity markets and the integration of variable REs, it is important to emphasize the different timescales of system operation, and operational and system planning. Whereas system operation has a timescale of seconds to days and focuses on the hour of operation, operational and system planning focuses on longer timescales. Operational planning covers a timescale of days to years, and system planning a timescale of 5 to 10 years and beyond.

In system planning the parameter of focus is system adequacy, i.e. the ability for the system to meet peak demand even under the most extreme condition. System adequacy is in turn related to the amount of installed capacity the system must have in order to maintain system reliability. Accordingly, long-term capacity planning and system adequacy assessments take place in order to meet long-term system requirements.

The project builds on system planning, security of supply and capacity credit concepts. As the capacity credit is related to firstly, system reliability, security of supply and system adequacy; and secondly, to long-term system planning, the capacity credit of a mix of RES in a Danish system will be studied. The assessment is done according to the definition provided by the International Energy Agency [1]: *"Capacity credit: the amount of power variable renewables can reliably be expected to produce at the times when demand for electricity is highest"*.

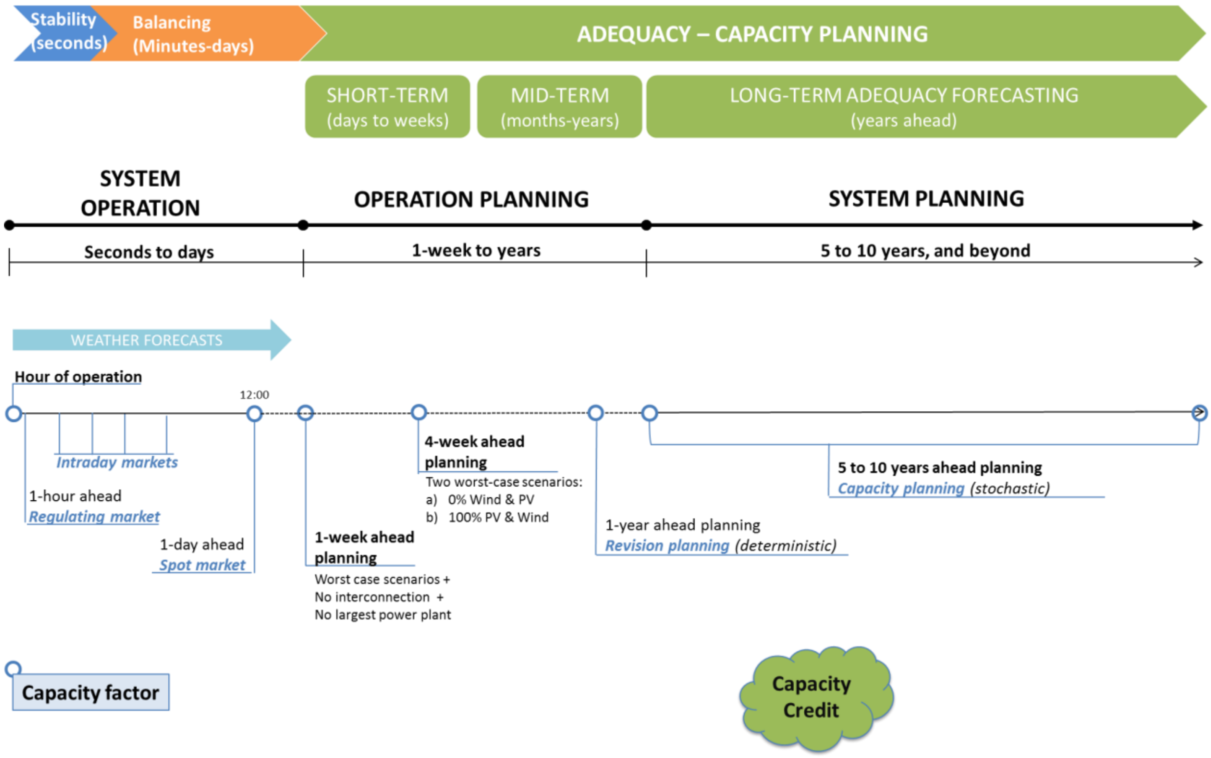


Figure 1. Timeline of electricity markets, the case of Denmark.

System Reliability and Security of Supply

Security of supply, system reliability and system adequacy are three terms referring to the same concept: maintaining a secure and trustable energy system. Any risks on system adequacy will have associated impacts on the security of supply of such system. For example, increasing production, increasing exchanges of electricity and reducing electricity consumption, all contribute to security of supply and to improve system reliability.

Particularly, system reliability refers to two different categories [2]:

c) Maintaining adequate system margin, also known as system adequacy, and
d) Balancing short term fluctuations, i.e. keeping the system in balance.

And accordingly, system operators are responsible of:

c) Ensuring security of supply of a system: they are responsible for maintaining system adequacy at a defined high level. In other words, they should ensure that the generation system is able to cover the peak demand, avoiding loss-of-load events, for a given security of supply.
d) They are also responsible for their area to be electrically stable, i.e. frequency to be kept at 50 Hz.

In consistence with the purpose of this study, system reliability refers to system adequacy and ensuring security of supply of the system.

The various national regulations regarding the level of security of supply range from a 99% security level to 91%. A 99% security level means that in 1 out of 100 years the peak load cannot be covered; this level is applied in Denmark, The Netherlands and Germany. A 91% security level translates into 1 event in 10 years, and is applied in the UK.

System Adequacy and Adequacy Estimations

System adequacy is the ability of the electricity system to meet electricity demand at all times with an acceptably high probability [1]. It measures the ability of a power system to cope with its load in all the steady states it may operate in under standard conditions [3].

This adequacy has different components [3]:

- Generation adequacy assessment: The ability of the generation assets to cover the peak load, taking into account uncertainties in the generation availability and load level; and
- Transmission adequacy assessment: The ability of the transmission system to perform, considering the flexibility provided by interconnection and import and export flows.

The assessment methods of generation adequacy can be deterministic or probabilistic, or a combination of both. System's adequacy is generally annually reviewed over a period of ten years. Generation adequacy assessment underscores how each country could satisfy its interior load with the available national capacity. In the adequacy estimation, each power plant is assigned a typical capacity credit. This takes into account scheduled and unscheduled outages. There are no plants with a capacity value of 100%, since there is always the possibility that capacity will not be available when required.

Traditional system adequacy analyses elaborated by the Danish Transmission System Operator (TSO) under the recommendations of the ENTSO-E (European Network of Transmission System Operators for Electricity), are carried out based upon the fact that conventional power plants have a positive capacity credit, i.e. can contribute to system's security of supply. On the other hand, the traditional general assumption in adequacy forecasts is that variable renewable generation cannot contribute to system adequacy (i.e. RES production equal to zero in hours of peak demand).

Capacity Credit and Capacity Factor

The capacity credit and capacity factor are both capacity related terms that represent different characteristics of power plants, and that appear in two very different timescales. The capacity credit is relevant in system planning (adequacy) whereas the capacity factor derives from the instantaneous operation of a power plant in every hour of operation.

Capacity Credit (CC): also known as capacity value, measures the contribution of a power plant to reliably meet demand [4]. It is measured either in terms of physical capacity (in MW) or the fraction of the power plant's rated capacity (%). The term also refers to the conventional thermal capacity that a variable generator can replace without compromising system reliability [5]. For example, a plant with 150 MW rated power and a capacity value of 50% could reduce the need for conventional capacity by 75 MW.

Results from regional system adequacy forecasts indicate that there is not yet a national TSO standard for the determination of RE's capacity credit [3], and different methodologies for its calculation are recommended [4, 5, 6, 7, 8]. In the study context, it is calculated as the amount of power variable renewable energies can reliably be expected to produce at the times when demand for electricity is highest [1, 4].

The Capacity factor (Cf) is a measure of the average production of a generation unit over a period of time with regards to its installed capacity. It is calculated as a percentage, by dividing the total energy produced during a period of time by the amount of energy the plan would have produced if it ran at full output during that time period [1]. Overall, the capacity factor is related to the operation of the generation unit. In case of conventional power plants and non-variable RES, the capacity factor is controllable to a large extent. For variable RES the capacity factor is only controllable in one direction, i.e. downwards.

Therefore, the capacity credit is related to the contribution that a generation unit can make to the security of supply and system adequacy of a given system, whereas the capacity factor is related to the operation of a unit as a measurement of its energy performance.

QUALITATIVE and QUANTITATIVE ASSESSMENTS

The aim of this section is to assess the contribution that variable renewable energies can have to security of supply. Firstly, the factors that can affect positively (i.e. can increase) the contribution that RES can have to security of supply are evaluated, and qualitative conclusions are derived. Secondly, the capacity credits of RES in different scenarios are calculated. Next section (Results and Discussion) relates and discusses both analyses.

The reference system and RES hourly distribution data files are the same for both assessments. They are presented here.

Reference system: Denmark is the reference system for the analyses, and year 2013 is the reference year. These have allowed having real hourly RES production data as input of the study. 2013 data have also served for calculating average annual Danish capacity factors of offshore wind (40%), onshore wind (25%), wave (32%) and solar PV (11%).

The Danish electricity system is characterized by high percentages of wind generation, high percentage of CHP (combined heat and power) plants, and strong interconnections to surrounding countries. The plan for future years (year 2020 and beyond) is having a system with higher penetrations of wind, small amounts of solar PV, stronger international connections, no diesel or coal power plants, and low capacity of gas turbines [9].

RES hourly distribution data files: Renewable energy sources included in the analyses are offshore wind, onshore wind, wave and solar photovoltaic. Hour by hour distributions of the different RES have been based on actual measurements whenever possible. For offshore wind, onshore wind and solar PV this has been the case. Data files are based on real hourly measured productions during year 2013, and they do take into account the spatial distribution of RES at a whole Danish level.

Such data do not exist for commercial wave energy farms. Consequently, wave production data have been generated from half-hourly wave measurements throughout year 2013 in two sites in the Danish North Sea, Hanstholm and Horn Rev 3. Having the significant wave height

(H_{m0}) and the wave period (T_{02}) as input values, the transfer function has been the Wavestar wave energy converter power matrix. Output values are hourly power production of Wavestar at the two selected locations. Based on these power productions, a distribution file representative of wave production data in the Danish North Sea has been created. Thus, the data file takes into account the spatial distribution of wave power along the Danish west coast, but it is not representative of the wave potential further offshore in the Danish North Sea.

Qualitative analysis

The factors that directly influence on the capacity credit of a given mix of RES in a given system are the following:

i) Correlation of RES production and demand
ii) Correlation among RES
iii) Diversification of the RES mix
iv) Geographical dispersion of each RES
v) Penetration level of the RES mix in the system
vi) Average capacity factors of the RES in the system

For the two first elements of the analysis the parameter cross-correlation coefficient is used. The cross-correlation coefficient evaluates the relationship between two different parameters, i.e. the degree to which the variation in one parameter is reflected in the variation of the other parameter. It varies in the interval [-1, 1], where <-1> indicates perfect negative correlation, <0> indicates no correlation and <1> indicates perfect positive correlation. The cross-correlation coefficient also allows evaluating the average delay between two set of values, which is the time lag (in hours) at which the cross-correlation coefficient reaches a maximum [10].

The concept of diversified renewable energy system refers to an energy system composed of various RES. The two key benefits of diversification are that the variability of the produced power can be decreased, and power availability can be increased [11, 12]. These benefits can be achieved by combining different resources, the more un-correlated the better. When only one resource is available these benefits can only be realised by aggregating the power of geographically disperse sites.

The opportunities that a diversified RES mix can bring are evaluated by the average number of hours per year of null or low production. This leads to some conclusions on the differences among individual RES productions and combined RES productions with regards to power availability.

Quantitative analysis

This study computes the capacity credit of a RES mix as the aggregated output of the RES mix in hours when demand for electricity is highest [1, 4]. Results are expressed as the fraction of the rated capacity of RES mix that adds to system reliability. The analysis is done over a year based on hourly values.

Study periods: as of interest to national TSOs and the ENTSO-E, this study examines how well the aggregated production of variable RES aligns with periods during which the system faces a high risk of an outage, i.e. periods of peak demand. Additionally, it is also of interest to investigate how RES production aligns with a subset of periods where electricity demand is low or RES production is high. Accordingly, the study focuses on four different periods (named as follows) during which:

- Electricity demand is maximum and RES production is minimum: Worst periods.
- Electricity demand is maximum: Peak demand periods.
- RE production is maximum: Hi-RES periods.
- RE production is maximum and demand is minimum: Best periods.

Time spans: nine different time spans are considered in the analysis of each study period. They are intended to represent the contribution of RES on an hourly basis, intra-day basis, intra-week basis, weekly basis, monthly basis and season basis. Time spans selected for the study are: 1-hour, 3-hour, 6-hour, 12-hour, 1-day, 3-day, 1-week, 1-month and 3-month. For every time span the average value for the indicated *consecutive* hours is measured (for example, the 3-hour value is calculated as the average value of 3 consecutive hours). Representative time spans do not necessarily need to be consecutive; this is, from the same day or hour as the immediately lower or higher time-span. The selected time span represents the consecutive averaged hour/hours in a year where the case of study occurs.

Definition of scenarios: for the purpose of the capacity credit analysis five future different scenarios with different mixes of RES are studied. Year 2030 is the study year and scenarios are based on CEESA2030 Scenario [13], which is constituted by the following features: total RES production of 27.38 TWh/y and total electricity consumption of 41.38 TWh/y, of which 21.85 TWh/y corresponds to classical electricity consumption, 3.93 TWh/y to flexible demand, 4.59 TWh/y to the electricity demand in the transport sector (i.e. electric vehicles), 3.66 TWh/y to consumption of industrial heat pumps, and 7.01 TWh/y to electrolysers and households' heat pumps and electric boilers. CEESA2030 Scenario is comprehensively described in [13] and is based on the smart energy design concept described in [14, 15, 16].

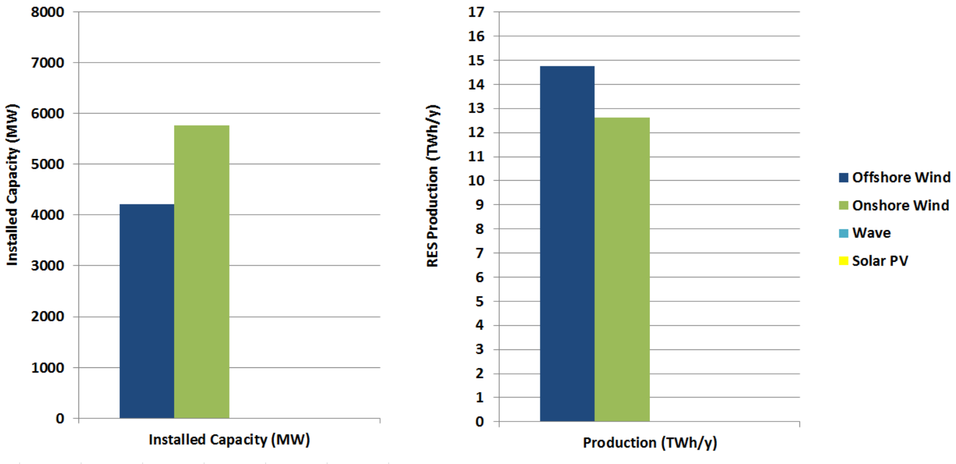
Scenarios are built based year 2013 data and on CEESA2030 Scenario. Scenarios are then designed as follows: annual total power production from RES is kept constant at 27.3 TWh/y (same value as in CEESA2030); production from offshore and onshore wind is kept equal or higher than 10.7 and 12.6 TWh/y, respectively, as defined by CEESA2030; and the or capacity factors of each technology are defined by 2013 values. Once productions of each RES are fixed and with the knowledge of the capacity factors, the installed capacity of each RES is calculated. Further information on how scenarios are built can be found in [17].

The five scenarios of the analysis are the following:

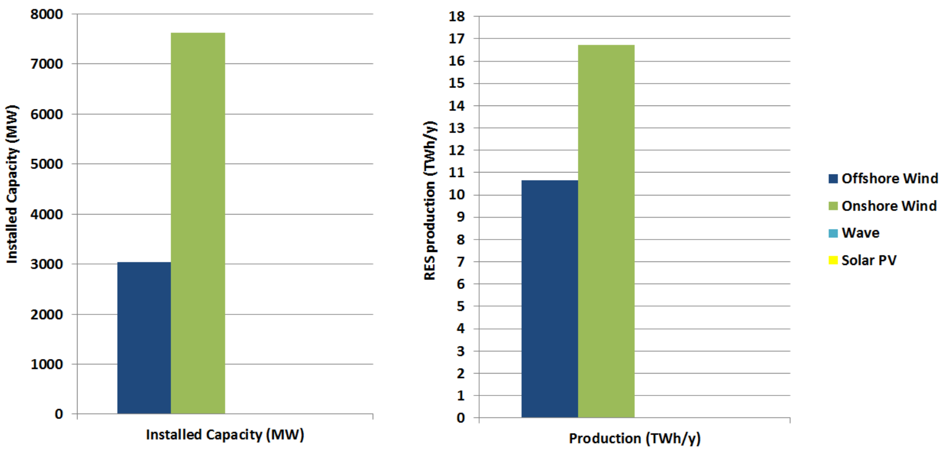
vii) Ambitious Offshore Wind Scenario
viii) Ambitious Onshore Wind Scenario
ix) Ambitious Wave Scenario
x) Ambitious Solar PV Scenario
xi) Combined RES Scenario

Some of these scenarios can indeed be compared to current and planned future Danish scenarios. The 'Ambitious Onshore Wind Scenario' can be compared to the RES mix in year 2013 in Denmark; the 'Ambitious Offshore Wind Scenario' is representative of ENS Wind 2035 scenario [9], and the 'Ambitious Solar PV Scenario' of CEESA2030 Scenario [13]. The installed capacity (in MW) and annual power production (in TWh/y) of each RES in each scenario are presented below:

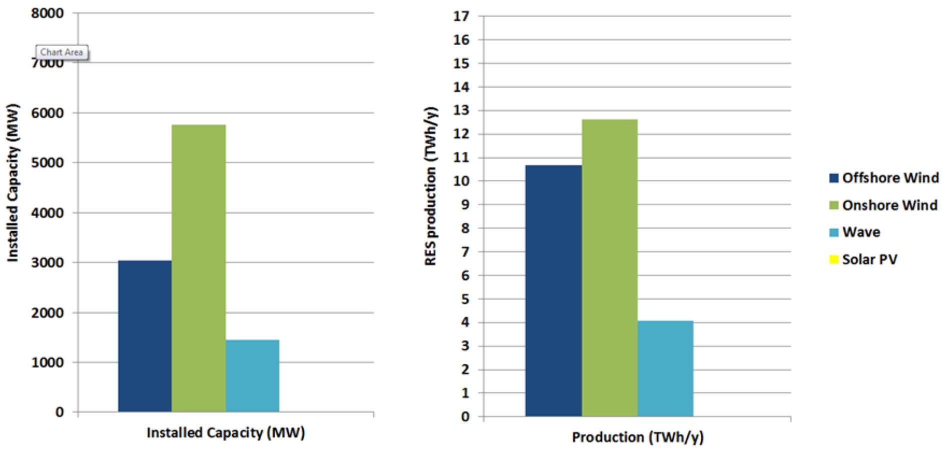
Ambitious Offshore Wind Scenario: in this scenario offshore wind power production is increased to a maximum value, onshore wind power production is kept at CEESA2030 values, and there is no production from wave or solar PV.



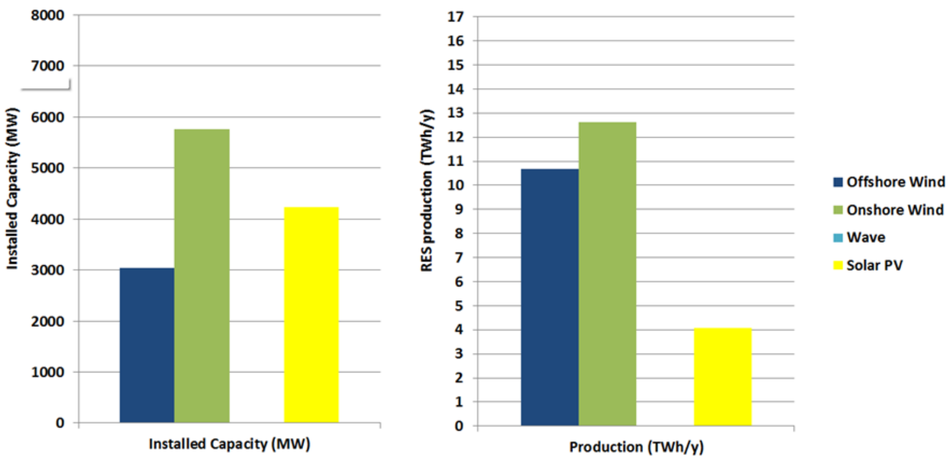
Ambitious Onshore Wind Scenario: in this scenario offshore wind power production is kept at CEESA2030 values, onshore wind production is increased to a maximum value, and there is no production from wave or solar PV.



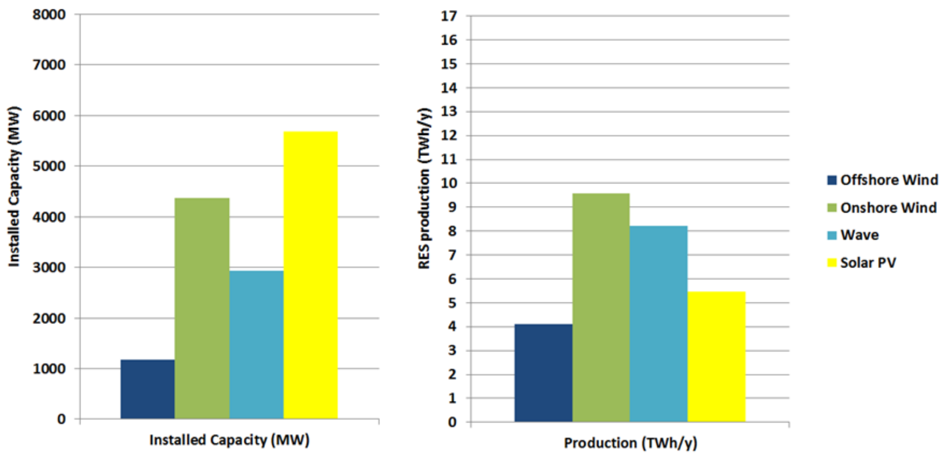
Ambitious Wave Scenario: in this scenario offshore and onshore wind productions are kept at CEESA2030 values, wave production is increased to 4 TWh/y (15% of total RES production), and there is no production from solar PV.



Ambitious Solar PV Scenario: in this scenario offshore and onshore wind productions are kept at CEESA2030 values, there is no production from wave energy, and solar PV production is increased to 4 TWh/y (15% of total RES production).



Combined RES Scenario: this scenario is defined based on the findings of [18], which to the authors knowledge, is the first Danish study looking into optimal combinations of the four RES of the project with high RES system penetration. The paper suggests an optimal mix of RES for Denmark when production from RES is above 80% of total production. Lund's analysis is done from a technical point view, where the optimisation parameter is the minimum excess production. In this scenario offshore wind produces 15% of the total RES production, onshore wind 35%, wave 30% and solar PV 20%.



System approach: Two system approaches to the capacity credit calculations are implemented: an electricity-only system approach and an integrated energy system approach. The two approaches consider much differentiated systems. The electricity-only system's approach looks into the electricity sector as an isolated energy system, whereas an integrated energy systems' approach is founded on a holistic system perspective that integrates the consumption in all energy sectors: transport, heat, industry and electricity.

The first approach responds to the traditional analysis, where the focus is put only on the classical electricity consumption. Besides classical electricity consumption, the second approach also takes into account flexible electricity consumption, electricity demand in the transport sector (i.e. electric vehicles), and consumption of industrial and household heat pumps, of electrolysers and households' electric boilers.

Electricity consumption hourly distribution data files: according to the description above two different electricity consumption patterns are utilised in the analysis: one representative of a classical electricity demand and another one illustrative of the electricity consumption in an integrated energy system. The first set of data has been directly obtained from [29]; it takes into account the spatial distribution of the electricity consumption at a whole Danish level and it only contains the classical electricity consumption projected for year 2035. The dataset representative of an integrated electricity consumption pattern is calculated as an output parameter of the EnergyPLAN model, as described below.

Model: two models are used for the analyses, an in-house model developed for the project and EnergyPLAN Model. The in-house model allows to calculating the individual and aggregated capacity credit of a given RES mix in a given system for all the time spans of the analysis [17]. Input data are hourly RES production and hourly electricity demand.

EnergyPLAN Model [19] is an advanced energy system's modelling tool for energy systems' analysis. It has been developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark. As a result, it is now a very complex tool which considers a wide variety of technologies, costs and regulations strategies for an energy system that includes heat and electricity supplies as well as the transport and industrial sectors. It is a deterministic input/output tool and general inputs are demands, renewable energy sources, energy station capacities, costs and a number of different regulation strategies for import/export and excess electricity production. Also, EnergyPLAN simulates the energy system on an hourly basis over one year. The hourly time-step is essential to ensure that intermittent renewable energy is capable of reliably meeting the demands for electricity, heat and transport. In the analysis a technical simulation strategy that balances both heat and electricity demands has been used.

RESULTS AND DISCUSSION

This section presents the set of results of the qualitative and the quantitative assessments.

Qualitative assessment of the factors that increase the Capacity Credit of RES

This section examines the cross-correlation of RES production and demand, and the cross-correlation among RES. The less correlated RES are to each other, the higher the capacity credit of the RES mix will be. With regards to the electricity demand it is the opposite; once RES are combined, the more correlated RES' production is to the electricity demand, the higher the capacity credit of the RES mix is.

Correlation of RES production and classical electricity demand: the cross-correlations at a 0-hour time lag between individual and combined RES production and classical electricity consumption are studied here; Table 1 presents the results.

Table 1. Cross-correlation factors between different scenarios of RES and electricity demand for a 0-hour delay. Numbers in brackets indicate RES production of [offshore wind - onshore wind - wave - solar PV], respectively.

Scenarios	Cross-Correlation
Year 2013 [1271 : 3531 : 0 : 478.3 TWh/y]	0.13
Ambitious Offshore Wind Scenario [14.8 - 12.5 - 0 - 0 TWh/y]	0.11
Ambitious Onshore Wind Scenario [10.7 - 16.6 - 0 - 0 TWh/y]	0.12
Ambitious Wave Scenario [10.7 - 12.5 - 4 - 0 TWh/y]	0.12
Ambitious Solar PV Scenario [10.7 - 12.5 - 0 - 4.2 TWh/y]	0.16
Combined RES Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]	0.17
Offshore Wind – Only	0.07
Onshore Wind – Only	0.14
Wave – Only	0.07
Solar PV – Only	0.13

Onshore wind and solar PV productions are the most correlated to the electricity demand, with cross-correlations of 0.14 and 0.13, respectively. Offshore wind and wave production are similarly cross-correlated with the electricity demand, with a value of 0.07. When RES are combined and independently of the RES mix analysed, generation and demand are positively correlated with values above 0.10 and below 0.20.

Among the scenarios studied, the highest cross-correlation factor is achieved by combining the four RES as in the Combined RES Scenario [18]. This scenario presents a cross-correlation factor of 0.17, which can be compared with the cross-correlation factor of RE production and demand in year 2013 of 0.13.

<u>Correlation among RES</u>: results are shown on Table 2, presenting the following findings: offshore wind, onshore wind and wave are highly correlated, and solar PV is uncorrelated. Offshore wind is high correlated to onshore wind production, i.e. a factor of 0.85, and the correlation is maximal for a zero-hour delay; there is also high correlation between wind and wave power production, which is explained by the fact that waves are created by winds; cross-correlation factors are between 0.6 and 0.7 for a zero-hour time lag. The average delay between wind and wave production is in between 1 to 2 hours for offshore wind production, and 1 to 4 hours for onshore wind production. On the other hand, solar PV is low correlated with offshore wind, onshore wind or wave production, presenting a low negative relatedness.

Table 2. Cross-correlation coefficient between two pair of RES. The maximum value is shown, as well as the delay, in hours, when correlation is maximum (in brackets).

	Offshore wind	Onshore wind	Wave	Solar PV
Offshore wind	1	0.85 (t=0 h)	0.68 (t=1-2 h)	-0.18 (t=1-2 h)
Onshore wind	-	1	0.61 (t=2-4 h)	-0.19 (t=8-9 h)
Wave	-	-	1	-0.18 (t=0-1 h)
Solar PV	-	-	-	1

As a result, the low correlation between solar PV production and wave or wind production, the average delay between waves and winds of 1 to 4 hours, and the higher correlation of solar PV and onshore wind with the classical electricity demand, benefits a RES generation mix with the four RES of the study. However, the cross-correlation factor does not assess the contribution of RES to security of supply. Further parameters are investigated to analyse this.

<u>*Diversification of the RES mix*</u>: the advantages of a diversified RES mix compared with an individual RES portfolio are investigated by examining the average number of hours per year i) with no production from RES, ii) with a production below 1% of maximum production, and iii) with a production below 5% of maximum production, for a subset of individual and combined RES scenarios.

Results for the individual RES scenarios are shown in Table 3.

Table 3. Average number of hours per year with different production patterns from individual RES.

Hours per year when,	Offshore wind	Onshore wind	Wave Prod.	PV Prod.
Production = 0	4 h/y	0 h/y	45 h/y	4232 h/y
Production <1% max. prod.	163 h/y	309 h/y	132 h/y	4613 h/y
Production <5% max. prod.	877 h/y	1505 h/y	1094 h/y	5509 h/y

Danish RES strategies envision scenarios with high penetrations of offshore and onshore wind, small amounts of solar PV and almost none wave power [9, 20, 21]. Provided that the Danish system will at least have a combined offshore and onshore wind RES system, the impact of including wave and solar PV in that mix is reviewed in Table 4.

Table 4. Average number of hours per year with different production patterns for different combinations of RES.

Hours per year when,	Off- and on-shore wind	Off- and on-shore wind, and wave	Off- and on-shore wind, and PV	Off- and on-shore wind, wave and PV
Production = 0	0 h/y	0 h/y	0 h/y	0 h/y
Production <1% max. prod.	519 h/y	251 h/y	376 h/y	190 h/y
Production <5% max. prod.	2786 h/y	2510 h/y	2424 h/y	2070 h/y

When RES are combined the hours with no production reduce to zero, i.e. there is RES production all hours during the study year. When wave and/or solar PV are added to the mix of offshore and onshore wind, the number of hours with low production decreases; and this is maximised when the four RES are combined together.

Other elements influencing the capacity credit of a given RES mix in a given system are the geographical dispersion of each RES and the penetration level of RES in the system. With regards to RES *geographical dispersion*, offshore and onshore wind are well-distributed over the whole Denmark, and this is the same for solar PV. The comparison between total wind production (aggregated production of off- and on-shore wind) in West and East Denmark shows an average delay between the two regions of 2-3 hours. For solar PV such an average delay does not exist. For wave energy the picture is different. Wave energy harnessing technologies will be placed in the Danish North Sea, i.e. West Denmark. Wave energy geographical dispersion can however be achieved by harnessing the waves of areas further offshore, i.e. up to 200 km offshore.

Current *penetration levels* of RES in Denmark are high (above 40% of total annual production), and projections aim for this number to increase. By 2020, 50% production from RES is projected, and by 2050 this number is expected to increase to 100%.

RE technologies average capacity factors in Denmark: background values of this project are year 2013 Danish capacity factors, where $Cf_{\text{offshore wind}}$ (40%) > Cf_{wave} (32%) > $Cf_{\text{onshore wind}}$ (25%) > $Cf_{\text{solar PV}}$ (11%).

The Danish TSO [20] and the Danish Energy Authority [9, 22] project an improvement of wind and wave harnessing technologies; and as such, their capacity factors are indeed expected to increase significantly. This is however not the case for solar PV. The capacity factor of solar PV might increase by 1% or 2% maximum, whereas a 5% to 10% increase is expected for offshore wind and wave technologies. Nevertheless there is higher uncertainty in the development of wave energy converters, and that justifies why capacity factors' estimates vary depending on the source. These improvements in technologies capabilities provide a different scenario as the one analysed in this paper. As examined here, the capacity factor affects directly on the capacity credit of RES. Thus, an improvement on RES capacity factors is expected to lead to higher capacity credits.

This is especially true for wave energy technologies, which are expected to greatly develop in the coming years [20] and also to be installed further offshore, covering deeper waters of the Danish North Sea. The most optimistic average power productions of wave energy reveal capacity factors higher than for offshore wind. If wave energy proves to have a higher or equal capacity factor than offshore wind, the picture of the aggregated capacity credit of RES can change positively. Overall, these developments will come along with higher contribution of RES to security of supply.

Quantitative assessment on the Capacity Credit of RES

This section presents the aggregated capacity credit of different mixes of RES for each of the four study periods, for each time span and calculated from two different approaches. A large number of results have been derived for this analysis [17] but due to space constraints only the most illustrative ones are presented here.

First, results derived from an electricity-only system approach are presented. Then, these are compared with results based on an integrated energy system approach.

Electricity-only system approach: Table 5 shows the capacity credit in five scenarios with different mixes of RES (as indicated by the numbers in brackets, which show the annual production of offshore wind, onshore wind, wave and solar PV, respectively) for four study periods and for various time spans. Capacity credit results can be read as the percentage of the total RES installed capacity available in that study period and at that time span.

Table 5. Capacity credit of RES expressed as the percentage of the total RES installed capacity, calculated from an electricity-only system approach. Results for different periods and time spans are shown. Numbers in brackets show the annual production of offshore wind, onshore wind, wave and solar PV in the chosen scenario. Five scenarios are shown.

Electricity-only System Approach - Ambitious Offshore Wind Scenario [14.8 - 12.5 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	1% ≤ CC ≤ 3%	9% ≤ CC ≤ 30%	98% ≤ CC ≤ 99%	90% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 4%	17% ≤ CC ≤ 27%	89% ≤ CC ≤ 93%	82% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 16%	15% ≤ CC ≤ 29%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 31%	31% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Electricity-only System Approach - Ambitious Onshore Wind Scenario [10.7 - 16.6 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 28%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 94%
12-hour to 24-hour	2% ≤ CC ≤ 3%	15% ≤ CC ≤ 25%	89% ≤ CC ≤ 92%	81% ≤ CC ≤ 85%
3-day to 1-week	6% ≤ CC ≤ 15%	13% ≤ CC ≤ 27%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 21%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Electricity-only System Approach - Ambitious Wave Scenario [10.7 - 12.5 - 4 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	3% ≤ CC ≤ 3%	8% ≤ CC ≤ 30%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 4%	16% ≤ CC ≤ 27%	81% ≤ CC ≤ 87%	78% ≤ CC ≤ 82%
3-day to 1-week	7% ≤ CC ≤ 16%	14% ≤ CC ≤ 28%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Electricity-only System Approach - Ambitious Solar PV Scenario [10.7 - 12.5 - 0 - 4.2 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 3%	8% ≤ CC ≤ 19%	71% ≤ CC ≤ 77%	67% ≤ CC ≤ 77%
12-hour to 24-hour	2% ≤ CC ≤ 3%	11% ≤ CC ≤ 18%	60% ≤ CC ≤ 63%	56% ≤ CC ≤ 59%
3-day to 1-week	5% ≤ CC ≤ 12%	10% ≤ CC ≤ 20%	41% ≤ CC ≤ 57%	41% ≤ CC ≤ 57%
1-month to 3-month	16% ≤ CC ≤ 22%	21% ≤ CC ≤ 22%	30% ≤ CC ≤ 36%	30% ≤ CC ≤ 36%

Electricity-only System Approach - Combined RES Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 4%	7% ≤ CC ≤ 18%	68% ≤ CC ≤ 73%	68% ≤ CC ≤ 73%
12-hour to 24-hour	3% ≤ CC ≤ 3%	10% ≤ CC ≤ 16%	53% ≤ CC ≤ 53%	53% ≤ CC ≤ 53%
3-day to 1-week	5% ≤ CC ≤ 11%	8% ≤ CC ≤ 17%	34% ≤ CC ≤ 46%	34% ≤ CC ≤ 46%
1-month to 3-month	15% ≤ CC ≤ 20%	19% ≤ CC ≤ 20%	27% ≤ CC ≤ 31%	27% ≤ CC ≤ 31%

The following findings can be derived from the tables:

How *worst periods, peak-demand periods, hi-RES periods* and *best periods* influence on the CC_{RESmix}:

- CC_{RESmix} in *worst* and *peak-demand periods*, and in *hi-RES* and *best periods*, respectively, follow the same trend. Minimum CC_{RESmix} appear for *worst* and *peak-demand periods*, and maximum CC_{RESmix} appear in *hi-RES* and *best periods.*

- *Worst periods*, which represent hours of maximum electricity demand and minimum RES production, show the hours where production of RES is minimal. Thus, the minimum CC_{RESmix} is derived, it being in the order of 1% of total RES installed capacity. This value increases to 4% when a time-span of 24-hour is chosen. *Peak-demand periods* show a CC_{RESmix} varying from 7% and 17% for 1-hour to 24-hour time spans, respectively.

- In *hi-RES periods and best periods*, i.e. hours of maximum RES production and minimum electricity demand, CC_{RESmix} can be as high as 99%.

- *Worst periods, hi-RES periods and best periods* sometimes occur in the same month of the year, in December month. *Worst periods* are mostly in January and also in February, sometimes in December too; p*eak-demand periods* are generally in January; *hi-RES periods* are generally in June, sometimes also in December; and *best periods* are generally in March, June and December months.

- Contrary to the traditional methodology utilised to derive CC values of RES, *worst hours* show less contribution from RES than in *peak-demand hours*. Thus, CC_{RESmix} in w*orst hours* are generally lower than in *peak-demand hours*.

How the time spans (1-hour, 3-hour, 12-hour, 24-hour, 3-day, etc.) influence on the CC_{RESmix}:

- There are significant differences among the capacity credits of the RES mix (CC_{RESmix}) throughout the studied time spans, i.e. on an hourly and intra-day basis, on a daily and intra-week basis and on a monthly basis.

- Generally, the CC of RES on an intra-day basis and on a daily basis differs in about 10 points, and the same trend appears when comparing the CC occurs when comparing the CC of RES on a daily basis and on a monthly basis. Therefore, the time span selected to calculate the CC_{RESmix} can have strong impact on the CC value CC used in the planning of the electricity system. These results invite to consider different timescales when evaluating the CC of RES, and to differentiate among a 'worst CC', 'reasonable worst CC', 'reasonable good CC' and 'best CC' for a given system, for example.

- The comparison between the 1-hour and the 24-hour time spans illustrates the difference between today's electricity system and future systems. Today's system is represented by the 1-hour condition, where demand does not follow production and peak hours are frequent. The future system is represented by the 24-hour averaged condition, where electricity consumption (loads) can be shifted throughout the day (in 12 to 24-hour periods) to hours where electricity demand is lower or RES production is higher, decreasing the stress over the system. By doing that: i) peaks in electricity consumption could be reduced, ii) 1-hour, 3-hour and 6-hour time spans would disappear, iii) and overall, as shown in the tables, CC_{RESmix} would increase. In other words, if peak demand hours were eliminated, the electricity consumption would respond to a more average and flat pattern, and there would be less demand peaks throughout the year. As a direct effect of this, the 1-hour to 6-hour time spans would disappear, and maybe also the 12-hour time span; and the contribution that RES could make to the system (the CC_{RESmix}) would be dictated by the value derived for the 24-hour time span.

How the RES mix, i.e. the scenarios of the analysis, influence on the CC_{RESmix}:

- Generally, CC_{RESmix} values are of the same range and follow the same trends for every scenario of the analysis.

- As a general trend $CC_{Offshore\ wind} > CC_{Wave} > CC_{Onshore\ wind} > CC_{Solar\ PV}$; and the CC of a RES mix is proportional to this relationship, it increases or decreases accordingly to the contribution of each RES in the mix. For example, increasing the amount of offshore wind or wave in a scenario increases the CC_{RESmix} more than if solar PV was added to that scenario. This can be seen by comparing the 'Ambitious Offshore Wind' or 'Ambitious Wave' scenarios with the 'Ambitious Solar PV' or 'Combined RES' scenarios.

- As in the current Danish system, which has significant offshore wind and onshore wind installed capacity, adding wave to the system would keep constant or increasing the CC_{RESmix}, and adding solar PV to the system would decrease the CC_{RESmix}.

<u>Integrated energy system approach</u>: Table 6 shows the capacity credit in five scenarios with different mixes of RES (as indicated by the numbers in brackets, which show the annual production of offshore wind, onshore wind, wave and solar PV, respectively) for four study periods and for various time spans. Capacity credit results can be read as the percentage of the total RES installed capacity available in that period and at that time span. Results are derived with EnergyPLAN energy system's model using a technical strategy that optimises, i.e.

minimises, fuel consumption, and adjusts demands according to what is possible with the installed technologies.

Table 6. Capacity credit of RES expressed as the percentage of the total RES installed capacity, calculated from an integrated energy system approach. Results for different periods and time spans are shown. Numbers in brackets show the annual production of offshore wind, onshore wind, wave and solar PV in the chosen scenario. Five scenarios are shown.

Integrated Energy System Approach - Ambitious Offshore Wind Scenario [14.8 - 12.5 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	4% ≤ CC ≤ 6%	77% ≤ CC ≤ 91%	98% ≤ CC ≤ 99%	90% ≤ CC ≤ 94%
12-hour to 24-hour	3% ≤ CC ≤ 3%	40% ≤ CC ≤ 59%	89% ≤ CC ≤ 93%	87% ≤ CC ≤ 93%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 22%	61% ≤ CC ≤ 85%	61% ≤ CC ≤ 85%
1-month to 3-month	23% ≤ CC ≤ 30%	30% ≤ CC ≤ 31%	44% ≤ CC ≤ 54%	44% ≤ CC ≤ 54%

Integrated Energy System Approach - Ambitious Onshore Wind Scenario [10.7 - 16.6 - 0 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	3% ≤ CC ≤ 5%	75% ≤ CC ≤ 90%	98% ≤ CC ≤ 99%	88% ≤ CC ≤ 94%
12-hour to 24-hour	2% ≤ CC ≤ 3%	38% ≤ CC ≤ 55%	89% ≤ CC ≤ 92%	86% ≤ CC ≤ 92%
3-day to 1-week	6% ≤ CC ≤ 18%	18% ≤ CC ≤ 21%	56% ≤ CC ≤ 83%	56% ≤ CC ≤ 83%
1-month to 3-month	21% ≤ CC ≤ 29%	29% ≤ CC ≤ 30%	41% ≤ CC ≤ 52%	41% ≤ CC ≤ 52%

Integrated Energy System Approach - Ambitious Wave Scenario [10.7 - 12.5 - 4 - 0 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	3% ≤ CC ≤ 5%	75% ≤ CC ≤ 79%	92% ≤ CC ≤ 93%	83% ≤ CC ≤ 90%
12-hour to 24-hour	2% ≤ CC ≤ 5%	42% ≤ CC ≤ 70%	81% ≤ CC ≤ 88%	78% ≤ CC ≤ 88%
3-day to 1-week	7% ≤ CC ≤ 19%	19% ≤ CC ≤ 24%	58% ≤ CC ≤ 81%	58% ≤ CC ≤ 81%
1-month to 3-month	22% ≤ CC ≤ 30%	30% ≤ CC ≤ 30%	43% ≤ CC ≤ 53%	43% ≤ CC ≤ 53%

Integrated Energy System Approach - Ambitious Solar PV Scenario [10.7 - 12.5 - 0 - 4.2 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 7%	60% ≤ CC ≤ 71%	75% ≤ CC ≤ 82%	71% ≤ CC ≤ 82%
12-hour to 24-hour	1% ≤ CC ≤ 4%	49% ≤ CC ≤ 52%	64% ≤ CC ≤ 67%	59% ≤ CC ≤ 63%
3-day to 1-week	8% ≤ CC ≤ 14%	14% ≤ CC ≤ 16%	44% ≤ CC ≤ 61%	44% ≤ CC ≤ 61%
1-month to 3-month	17% ≤ CC ≤ 23%	22% ≤ CC ≤ 23%	32% ≤ CC ≤ 38%	32% ≤ CC ≤ 38%

Integrated Energy System Approach - Combined RES Scenario [4.1 - 9.5 - 8.1 - 5.6 TWh/y]				
	Worst periods	**Peak demand periods**	**Hi-RES periods**	**Best periods**
1-hour to 6-hour	2% ≤ CC ≤ 7%	55% ≤ CC ≤ 65%	73% ≤ CC ≤ 78%	73% ≤ CC ≤ 78%
12-hour to 24-hour	3% ≤ CC ≤ 6%	30% ≤ CC ≤ 48%	57% ≤ CC ≤ 57%	57% ≤ CC ≤ 57%
3-day to 1-week	8% ≤ CC ≤ 13%	18% ≤ CC ≤ 33%	37% ≤ CC ≤ 49%	32% ≤ CC ≤ 49%
1-month to 3-month	16% ≤ CC ≤ 21%	20% ≤ CC ≤ 21%	29% ≤ CC ≤ 34%	24% ≤ CC ≤ 26%

Influence on the approach (electricity-only or integrated energy system) to the CC_{RESmix}

It is of much interest to investigate if the capacity credit of the renewable energy portfolio of focus changes when modelling it within an electricity-only system or in an integrated energy system.

The biggest difference when modelling an electricity-only system or an integrated energy system is in the capacity credit of *peak-demand periods*. Particularly, for the capacity credits within the intra-daily time-scale, i.e. in the interval 1-hour to 24-hour. In these time spans, the capacity credit of the RES portfolio increases, reaching almost the capacity credits of the *hi-RES periods*. The raise is highest for the smallest time span (i.e. 1-hour) and it is less pronounce as the time span increases. However, CC_{RESmix} improves only slightly for the w*orst periods* in the 1-hour to 24-hour time spans. This can be explained by the fact that in *worst periods* RES production is minimum, and therefore there is no opportunity in the system to transfer the electricity production from RES to other hours. In an integrated system it will be possible to (and indeed EnergyPLAN model does so) shift peak-demand hours to hours where RES production is high, and the direct results of that approach can be seen here. By implementing an integrated energy system approach, the CC of RES in *peak-demand periods* increases significantly and it almost reaches the values achieved in *hi-RES periods* and *best periods.*

For daily, weekly and monthly time spans, the CC_{RESmix} does not change significantly if modelling an electricity-only system or an integrated energy system. This can be explained by the fact that integrated energy systems have a smoothing effect with regards to the integration of RES on the intra-day timescale.

In those scenarios where there is significant solar PV installed, the CC_{RESmix} in all time spans increases when an integrated energy system approach is used. In other words, when the RES portfolio includes a high percentage of solar PV production (10% to 20% of total RES production), the contribution of RES in *periods of peak-demand* and in *worst periods* proves to be higher if an integrated energy system approach is used.

The comparison in numbers among CC values achieved with an electricity-only system approach and an integrated energy system approach are the following:

- Minimum, maximum and average CC_{RESmix} values depend on the periods considered: worst periods, peak-demand periods, hi-RES periods or best periods.

- In an electricity-only system, the minimum aggregated contribution that RES can have in *worst periods* is 1% to 3% and occurs for the 1-hour time span. Also in worst periods but for 3-month time spans, CC_{RESmix} increases to 20%-31%. Also for the worst periods, these numbers increase slightly in an integrated energy system, rising to 2% to 4% for the 1-hour time span.

- Peak periods do not coincide with minimum CC values. In an electricity-only system the CC during *peak-demand periods* range 7%-9% for the 1-hour interval to 16%-27% in the 24-hour interval. Numbers do change significantly in an integrated energy system and increase to 55%-77% for the 1-hour interval to 48%-70% in the 24-hour interval.

- Maximum contributions that RES can have happens on *best periods* and for the 1-hour time, and are up to 70-80-99% depending on the RES mix. As expected values lower a bit in an integrated energy system.

- The average contribution that can be expected from RES in worst and peak demand hours on a monthly average varies in the range 15% - 31%, depending on the scenario (the more offshore wind and wave installed in the system, the higher the CC, and the opposite is true for onshore wind and solar PV). This is true in both an electricity-only and in an integrated energy system. The average CC_{RESmix} is close to the average capacity factor of the RES mix during the period of consideration, which is line with [5], who state that the CC of a RES mix can at most equal the Cf of the RES mix.

- If the daily average is considered instead, the overall average CC_{RESmix} in worst and peak demand hours varies in the range 3% - 27%, depending on the scenario, in an electricity-only system; and 3% - 70% in an integrated energy system. Here, the positive effects of an integrated energy system can be clearly seen. Integrated energy systems need however to be further developed, where components from all sectors will be able to contribute to the system electrical balance and hence increase the CC of the mix of RES [23].

CONCLUSIONS

The following is a set of suggestions on how to evaluate the contribution that RES can make to security of supply, i.e. on the evaluation of the parameter CC_{RESmix}. These recommendations aim to go beyond the traditional approach used in adequacy forecasts to meet security of supply.

The methodology traditionally used by TSOs, the ENTSO-E and the IEA to calculate the capacity credit of RES does not seem suitable when variable RES are part of the electricity generation mix. Accordingly, an approach has been developed that looks into the capacity credit of a RES mix for different time spans (intraday, intraweek, intermonth and seasonally) and key time periods during a year (worst, peak-demand, high RES and best periods), and not only during the 10^{th}-100^{th} highest consumption hours during a year.

The following recommendations might be taken as part of a new methodology:

- Investigate RES production throughout key time periods during a year, instead of only calculating RES production during a given number of highest consumption hours of a year.

- Examine RES production throughout different time spans taking into account intra-daily and daily averages in consumption. This is especially important as changes in demand patterns are expected and peak demand hours might be shifted to other hours in the day where demand is lower or RES production is higher.

- Evaluate RES production from an integrated energy system approach and not only based on classical electricity consumption. As decisions in 20-30 year time are happening now, it is important that this decision's processes take into account changes in demand patterns, as well as changes on how the electricity and the other energy sectors (transport, heat and industry) will interact. This is addressed in this study by implementing an electricity-only system and an integrated energy system; and differences of using one and the other have been shown.

- Two very different periods should be distinguished: *worst periods* and *peak-demand periods*. Whereas on the former RES production is minimum and peak demand is maximum, the latter only takes into account periods of peak demand. Therefore, *worst* *periods* are interesting to study how the whole system (with minimum amounts of RES) can meet security of supply, and *peak-demand periods* to study what can the contribution of RES be in periods when electricity consumption is highest.

- In today's Danish electricity market there is no capacity market for RES. After the research carried out in this project, the question on whether a positive capacity credit can be related to a capacity payment arises. Can a capacity credit above zero be related to any money scheme for the RES of focus? This would indeed allow companies and individuals who invest in RES to have an energy payment and a capacity payment. If the Danish goal is to be a fossil free nation in 2050, it might not be too early to discuss such a tariff system. The discussion could also address whether capacity payments should be part of long-term system planning or of system operation.

Overall, the contribution that can be expected from RES averaged over a month is in the range of 15% to 30%, depending on the scenario. The more offshore wind and wave installed in the system, the higher the capacity credit of the RES mix, and the opposite is true for onshore wind and solar PV.

In addition, the Danish TSO [20] and the Danish Energy Authority [9, 22] project an improvement of wind and wave harnessing technologies; and as such, their Cf are expected to increase significantly. These improvements provide a different scenario as the one analyzed in this paper, and this is especially true for wave technologies, which in some scenarios are projected to have capacity factors higher than offshore wind. If this proves true, the picture of the aggregated capacity credit of RES can change positively. Overall, technology developments will come along with higher contribution of RES to system adequacy.

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REFERENCES

1. OECD/IEA. "World Energy Outlook". Organisation for Economic Co-operation and Development /International Energy Agency (OECD/IEA), 2011.
2. UKERC. "The Costs and Impacts of Intermittency". UK Energy Research Centre (UKERC), 2006.
3. EWEA. "Wind Energy The Facts". European Wind Energy Association (EWEA), 2009.
4. NREL. "Using wind and solar to reliably meet electricity demand". National Renewable Energy Laboratory (NREL), NREL/FS-6A20-63038, 2015.

5. Gross, R; Heptonstall, P; Leach, M; Anderson, D; Green, T and Skea, J. “Renewables and the grid: understanding intermittency”. Energy 160, Proceedings of the Institution of Civil Engineers, 2007, pp. 31-41.
6. Stoutenburg, ED, Jenkins, N and Jacobson, MZ. “Power Output Variability of Co-located offshore wind turbines and wave energy converters in California”. Renewable Energy, 2010.
7. Giebel, G. “Wind power has a capacity credit – A catalogue of 50+ supporting studies”. Wind Eng E Journal, 2005.
8. OECD/IEA. “World Energy Model - Modelling the capacity credit of renewable energy sources”. Organisation for Economic Co-operation and Development /International Energy Agency (OECD/IEA), 2011.
9. Energistyrelsen. “Energiscenarier frem mod 2020, 2035 og 2050 (Energy Scenarios for 2020, 2035 and 2050)”. Energistyrelsen (Danish Energy Authority), 2014.
10. Fusco, F, Nolan, G and Ringwood, JV. “Variability reduction through optimal combination of wind/wave resources - An Irish case study”. Energy 35, 2010, pp. 314-325.
11. Fernández-Chozas, J. “Technical and Non-technical Issues Towards the Commercialisation of Wave Energy Converters”. PhD Thesis (DCE Thesis no. 44), Aalborg University, 2013.
12. Fernández Chozas, J., Sørensen, H.C. and Kofoed, J.P. “Final project report: Analysis of Power Output Predictability of Wave and Wind”. Energinet.dk, PSO project 10791, 2013.
13. Lund, H, Hvelplund, F, Mathiesen, BV, Østergaard, PA, Christensen, P., Connolly, D., et.al. “Coherent Energy and Environmental System Analysis”. Aalborg University, Department of Development and Planning, Technology, Environment and Society, 2011.
14. Mathiesen, B. V., Lund, H. and Karlsson, K. “100% Renewable energy systems, climate mitigation and economic growth”. Applied Energy, 88(2), 488-501. 10.1016/j.apenergy.2010.03.001, 2011.
15. Lund, H., Andersen, A. N., Østergaard, P. A., Mathiesen, B. V., and Connolly, D. “From electricity smart grids to smart energy systems: A market operation based approach and understanding”. Energy, 42(1), 96-102, 2012.
16. Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P. A., Möller, B, et al. “Smart Energy Systems for coherent 100% renewable energy and transport solutions”. Applied Energy, 145, 139–154, 2015.
17. Fernandez-Chozas, J. “Capacity Credit of Wind, Wave and Solar PV. Final Project Report”. Energinet.dk PSO-ForskVE-12134, Available at www.juliafchozas.com/projects/, 2015.
18. Lund, H. “Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply”. Renewable Energy 31, 2006, pp. 503-515.
19. EnergyPLAN. “EnergyPLAN: Advanced Energy System Analysis Computer Model”. Aalborg University. Available from www.energyplan.eu, 2015.
20. Energinet.dk. “Energi 2050 – Vindsporet”. Energinet.dk, Dok.6357/11, Sag 10/3378, 2011.
21. Energinet.dk . “Energinet.dk’s analyseforudsætninger 2014-2035”. Energinet.dk, 2015.
22. Energistyrelsen. “Technology Data for Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion”. Energistyrelsen (Danish Energy Authority), 2012 with updates.
23. Mathiesen, B. V. and Lund, H. “Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources”. IET Renewable Power Generation, 3(2), 190-204, 2009.