TKI WIND OP ZEE
Topsector Energie

TNO innovation for life

Analysis of wind and solar generation profiles for multi-use offshore wind farms

By TNO

Commissioned by RVO and TKI Wind op Zee

June 2022

Task commissioned by RVO and TKI Wind op Zee

TNO is delighted to respond to the request to analyze generation profiles for multi-use offshore wind farms.

The TKI Wind op Zee required an analysis of combined offshore energy generation profiles and the potential impact on the combined business cases for the offshore wind energy in connection with offshore solar energy. This with an interest in future R&D direction.

The concise assignment consists of four activities, following the structure of the RFQ:

- Activity 1: Generation profiles for offshore wind energy and offshore solar energy for the Dutch economic zone of the North Sea.
- Activity 2: Impact on the business case of combining offshore wind and offshore solar energy.
- Activity 3: Impact of combining offshore wind energy and offshore solar energy technologies on the balancing costs of the grid.
- Activity 4: Impact of combining offshore wind energy and offshore solar energy technologies on the required optimal capacity of the Tennet infrastructure.

This report may be published in its entirety and not split.

Disclaimer

This report was commissioned by RVO (Netherlands Enterprise Agency) at the request of the TKI Wind op Zee (TKI Offshore Wind). The opinions expressed in this report are entirely those of the authors (TNO) and do not reflect the views of the TKI Wind op Zee. TKI Wind op Zee is not liable for the accuracy of the information provided or responsible for any use of the content.

Reader notes

Before reading either the summary or full report please take the time to read the pre-read information on the next two slides. In particular the starting points and assumptions used in the study are essential to understand before drawing conclusions from this work.

Furthermore a summary of the activities and key take-aways are presented initially. For an in-depth understanding of the study, its approach, results, conclusions and recommendations for future work, the authors advise to read the full report.

Pre-read

Background and research goals

One of the forms of multi-use is to include other renewable electricity generation technologies such as floating solar energy within the wind farm area and sharing the electrical infrastructure and grid connection. The generation profiles of offshore renewable energy technologies differ from the generation profile of offshore wind. The combination of these different profiles may bring benefits of higher utilization of the electrical infrastructure, and a more constant generation profile of the combined technologies. However, there can also be negative impact due to curtailment in periods where the combined production exceeds the nominal capacity of the grid connection. The costs associated with certain technologies may be another challenge for deployment.

This study aims to identify whether the combination of offshore wind farms with floating solar energy in different forms and with shared infrastructure, can bring benefits to the system. It may provide more stable and higher baseload power supply, or negative impact - due to curtailment in periods exceeding the capacity of the grid connection with higher associated costs.

Using realistic and measured time series of wind speed and solar irradiation driving renewable electricity production at a representative location, the following activities are performed:

1. Offshore generation profiles for wind energy and floating solar for the Dutch economic zone of the North Sea.
2. Impact on the business case of combining offshore wind and floating solar energy technology.
3. Impact of combining offshore wind energy and floating solar energy technology on the balancing costs of the grid
4. Impact of combining offshore wind energy and floating energy technology on the required optimal capacity of the TenneT infrastructure.

Pre-read

Starting considerations and assumptions used in the study

- A single site in the Dutch North Sea is selected, assumed to be representative for existing and future Dutch wind farms and their climatological conditions. To have a representation of the entire Dutch North Sea, additional sites spread over the area should be considered and at least 30 years period to capture climate variability.
- This study focuses on offshore combined technologies, which are assumed to operate as a single asset, utilizing the same substation and export cable. Dynamic (over)loading of the cable is not considered in the study.
- The cost considerations in this study are based on the expected LCOE for the considered years, extracted from robust literature sources.
  - LCOE values assumed do not account for potential cost reductions of the combined technologies, such as sharing of equipment, infrastructure or operation and maintenance (O&M) activities.
  - The LCOE values assume fixed Annual Energy Production (AEP). It does not include the reduction of AEP as a result of curtailment in a dynamic way.
  - Sharing of the export infrastructure with offshore wind is critical consideration. Including this cost in the LCOE of solar technology results in a decrease in NPV with respect to the reference case in 2030 scenario. However, in the 2050 scenario, since the solar LCOE is assumed significantly reduced with respect to the costs in the 2020 scenario, the NPV shows a positive business case.
- The main drivers for all profitable cases are the steep decrease in LCOE of floating Solar and higher future market prices compared to the 2020 scenario. Deviation from the considered assumptions and trends will therefore impact the profitability.
- Mutual interaction between the assets, such as the solar PV influence on the wind turbulence and resulting wind speed, or wind farm shadow (dynamic and static) on PV panels, are not considered in this analysis. The inclusion of these effects in the analysis will provide a more complete view of the combined generation profile.

Summary

Activity 1 – Generation profiles

Deliver generation profiles for offshore wind energy and offshore solar for a location in the Dutch North Sea. A location close to the Gemini and Ten Noorden van de Wadden (TNvdW) wind farms is selected, as representative for existing and future Dutch wind farms and climate of the Dutch North Sea.

Met-ocean data for a period of 10 years (2008 to 2017) at 1-hour frequency is used for an accurate representation of the conditions at this location, that also captures the short-term climatic variability.

Source: https://english.rvo.nl/sites/default/files/2020/07/Dutch-Offshore-Wind-Farm-Zones-VJuly2020.pdf

Summary

Activity 1 – Key takeaways

Offshore wind with offshore solar generation profiles

- The correlation of wind and solar power is negative annually, that is, when wind power increases, solar power decreases and vice versa. This effect can more closely approximate baseload generation and potentially reduce the amount of curtailment required for a combined wind and solar generation. The negative correlation does not follow any seasonal or monthly pattern, but it is observed during short periods of several consecutive days (see Annexes for more detailed correlation analysis).

Summary

Activity 2 – Combined technologies & business case impact

This activity determines the impact of combining offshore wind with offshore solar energy on the business case, expected curtailment and export cable utilization rate. The net present value (NPV) of different combinations of installed capacity for the considered technologies is calculated. Estimated future power market prices and projected levelized cost of energy (LCOE) are used for 2020, 2030 and 2050, based on TNO internal models and scenarios, aligned with national targets.

The combined business cases are assessed using combined generation hourly duration curves, considering different installed capacities when combining solar energy with a 1GW wind farm. The duration curves are used to determine the increase in baseload generation, export cable utilization and curtailment for different installed capacities of the technologies.

The NPV is calculated using the combined generation hourly profiles, estimated future market prices and LCOE values of the technologies for three scenarios selected for 2020, 2030 and 2050. The NPV for each combined business case is compared with the reference case (wind farm of 1 GW) for the three periods selected to analyse whether the profitability increase. The table below shows the combinations of the business cases applicable for the three scenarios.

NPV for each combined business case, hourly generation profiles	50MW	250MW	500MW	750MW	1000MW
Ref. (Offshore Wind Farm)	Wind: 1000 MW	Wind: 1000 MW	Wind: 1000 MW	Wind: 1000 MW	Wind: 1000 MW
OFW+ solar	Wind: 1000 MW Solar: 50 MW	Wind: 1000 MW Solar: 250 MW	Wind: 1000 MW Solar: 500 MW	Wind: 1000 MW Solar: 750 MW	Wind: 1000 MW Solar: 1000 MW

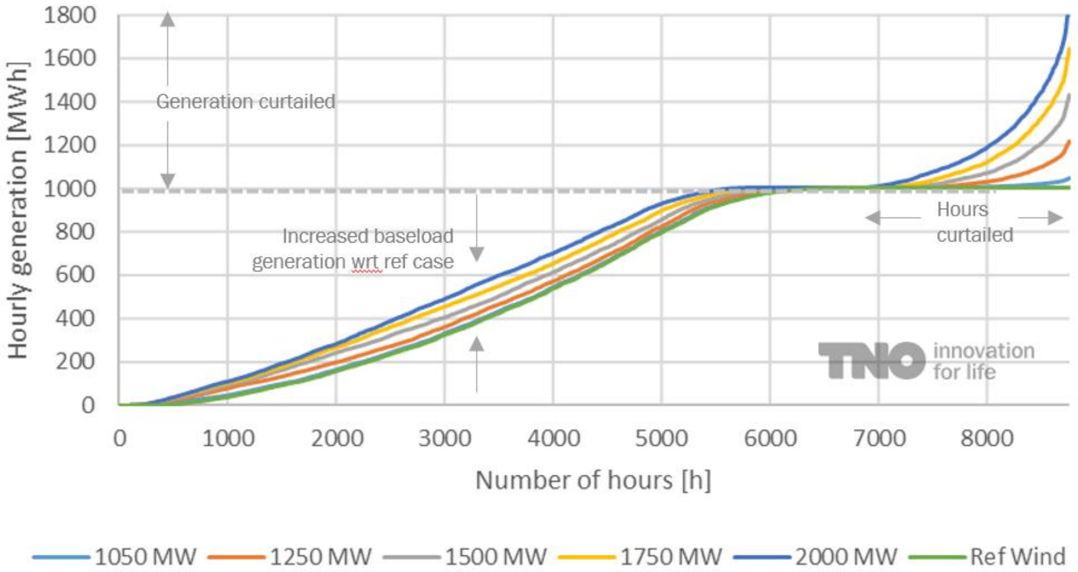
Summary

Activity 2 – Key takeaways

Offshore wind connected with floating solar: impact on total generation and export cable utilization

- The addition of 1 GW floating solar PV to 1 GW offshore wind increases the total exported generation and utilization rate of the export cable by up to 13%, while curtailment is limited to 6% of the total annual generation in this case. For any capacity of solar PV (up to 1 GW) connected with 1 GW of offshore wind, the curtailment is less than 50% of their total generation.
- To reach the 13% increase in export cable utilization by connecting 1 GW of floating solar to 1GW wind farm, a total of 29 additional wind turbines would be needed with a total installed capacity of 1.44 GW. This configuration would curtail 20.7% of the total annual generation, assuming the 1 GW of export cable. Therefore, the addition of solar PV with the objective of increasing the cable utilization is more beneficial than installing additional wind capacity, also from a curtailment perspective.

The duration curve figure shows the hourly generation profiles of the wind (green) and different capacities for solar (other colors). Each hourly generation profile time series, of a full year (2017) is sorted from lowest to highest hourly generation, and plotted to show the correlation between the hourly generation and its occurrence throughout the year.
Plotting this time series yields the number of hours in the year where the production of the considered asset is above (towards right)/below (towards left) the corresponding hourly generation
For a more detailed explanation on these figures, please refer to <u>Annex 1</u>.



Summary

Activity 2 – Key takeaways

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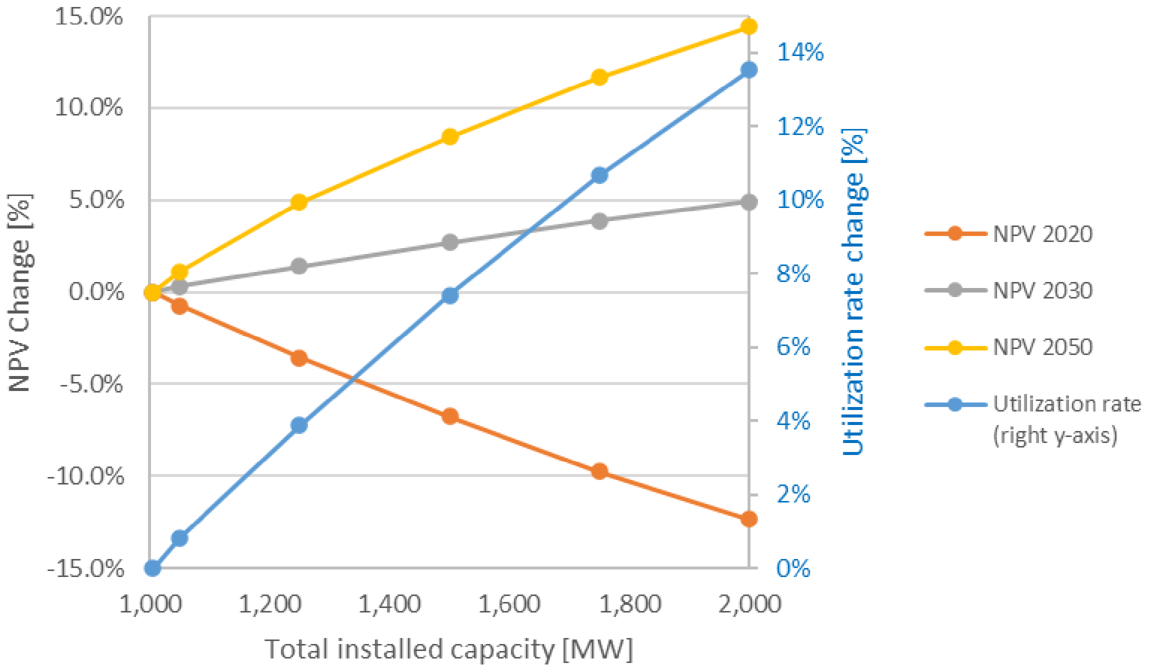
Offshore wind connected with floating solar: impact on the combined NPV

- Combining 1 GW offshore wind with any capacity of floating solar shows an increase in NPV of the combined asset from 2030 onward compared to the reference wind case, assuming shared infrastructure between wind and solar.
- The NPV improves further towards 2050, mainly due to reduction of LCOE for solar PV. In the 2020 scenario, the addition of any capacity (up to 1 GW) of floating solar to offshore wind results in a decrease in NPV, with the total cost higher than revenues.

LCOE [€/MWh]	2020	2030	2050
Wind (incl. export cable)	55.5	42.2	30.2
Solar PV (excl. export)	87.4	60.0	31.4

This figure shows the change in NPV and export cable utilization rate due to the combination of different technologies. On the left axis, the change in NPV from the reference wind case (installed capacity 1000 MW) is shown for different combined installed capacities. The right axis (in blue) shows the increase in utilization of the export cable due to the combined technologies.

For a more detailed explanation on these figures, please refer to Annex 1.



Summary

Activity 3 – Grid balancing cost

- Study the impact of combining 1 GW of offshore wind energy with offshore solar on the balancing cost of the grid. A positive impact is given by the case that reduces the variability of the supplied generation, and more closely approximates baseload generation.
- The imbalance costs are added to the selected combined business cases when the generation is increased with respect to the reference case.

Summary

Activity 3 – Key Takeaways

- The combined business cases are the wind farms connected with 1 GW of floating solar, which shows increasing revenues from 2030 onwards.
- The addition of 1 GW of floating solar PV to the reference 1 GW wind farm will lead to a reduction in variability of generation and increase in utilization of the 1 GW export cable from 58% to 65%, thereby more closely approach baseload generation.
- The imbalance caused by the variability of the wind may be further reduced by considering storage options, shifting the moment where the power is entering the grid, and also reducing the amount of curtailment. Such storage options can also provide further controllability over the combined wind and solar case than the case of connecting wind to the solar.
- The negative correlation found between wind and solar may be not enough to increase baseload generation and avoid imbalances or smoothening the variability of the wind. A comparative study between the combined case and storage option for imbalance should be considered to determine the most beneficial option.

A detailed description of Activity 3 can be found in Section 3 of the main report.

Summary

Activity 4 – Optimal export infrastructure capacity

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- Analysis of the impact of combining 1 GW offshore wind energy with offshore solar on the required optimal capacity of the export infrastructure, from a base case of a 1 GW export cable. The 2050 scenario was selected as a reference, since it showed the best combined business case of solar PV and wind.
- The required curtailment and resulting NPV of the combined case in the 2050 scenario is estimated. This estimation is performed for different export infrastructure capacities, accounting for the cost associated with expansion of this infrastructure and the increased revenue from energy that would otherwise be curtailed (value of curtailed energy). Two cases for the export cable capacity are considered; total export capacity of 1.4 GW and 1.8 GW.

Summary

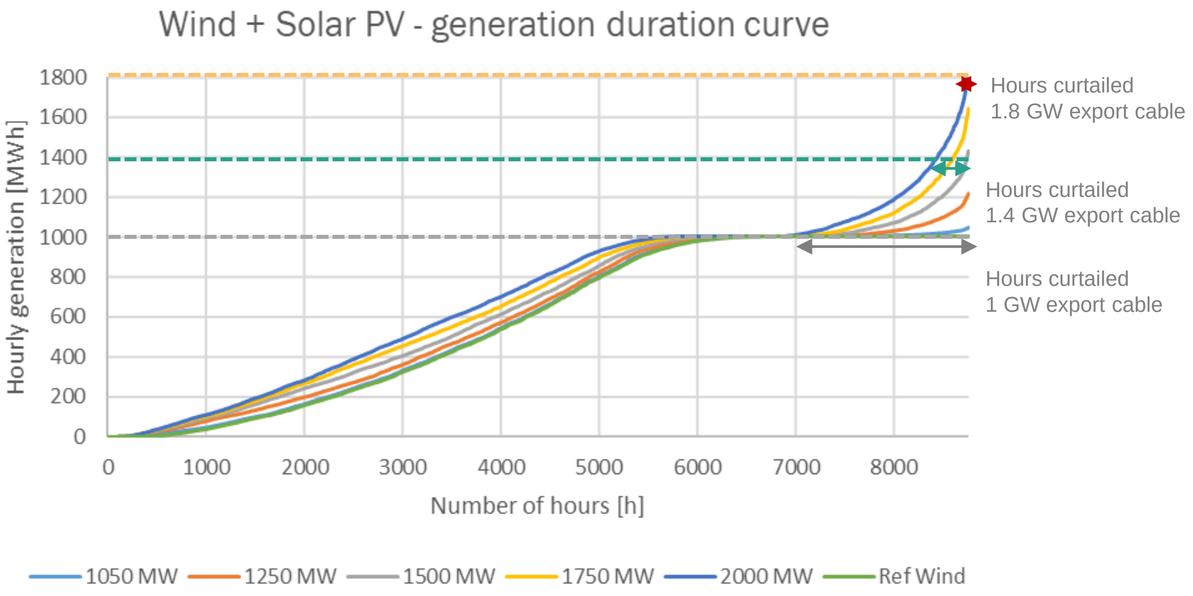
Activity 4 – Optimal export infrastructure capacity

Export cable	Statistics	Solar - 50 MW	Solar - 250 MW	Solar - 500 MW	Solar - 750 MW	Solar - 1000 MW	Reference Wind
-	Total generation [GWh]	5156	5369	5635	5901	6168	5102
1 GW	Curtailment [GWh]	11	68	155	255	375	-
	Share of curtailed energy [%]	0.22%	1.27%	2.75%	4.31%	6.08%	-
	Frequency of curtailment [h]	1130	1364	1516	1670	1855	-
	Value of curtailed energy [M€]	**2.1**	**14.2**	**34.1**	**55.8**	**80.0**	-
	NPV [M€]	**407.9**	**423.0**	**437.4**	**450.4**	**461.5**	403.4
1.4 GW	Curtailment [GWh]	0.0	0.0	0.2	13.4	50.1	-
	Share of curtailed energy [%]	0.00%	0.00%	0.00%	0.23%	0.81%	-
	Frequency of curtailment [h]	0	0	14	151	317	-
	Value of curtailed energy [M€]	**0.0**	**0.0**	**0.0**	**4.4**	**17.1**	-
	NPV [M€]	**408.9**	**431.1**	**458.7**	**482.7**	**499.3**	403.4
1.8 GW	Curtailment [GWh]	0.0	0.0	0.0	0.0	0.4	-
	Share of curtailed energy [%]	0.00%	0.00%	0.00%	0.00%	0.01%	-
	Frequency of curtailment [h]	0	0	0	0	12	-
	Value of curtailed energy [M€]	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	-
	NPV [M€]	**408.1**	**427.2**	**450.9**	**474.7**	**498.5**	403.4

Summary

Activity 4 – Key Takeaways

- The increase of export cable capacity from 1 GW to 1.4 GW has a positive effect on the NPV of the combined 1 GW wind and 1 GW solar case with respect to the reference of only 1 GW of wind. It is economically positive since the NPV increases by 8% and the value of curtailed energy decrease by 78% between the 1 GW and 1.4 GW export capacities.
- Increasing the export cable capacity from 1.4 GW to 1.8 GW reduces curtailment to (almost) zero for all cases. However, it is not economically beneficial, since the NPV decreases compared to the 1.4 GW scenario, indicating that the revenue from avoided curtailment no longer outweighs the additional infrastructure cost.
- There is a benefit in expanding the export infrastructure to accommodate additional solar PV generation. However, the additional export capacity does not have to match the total combined capacity since the costs of the export cable are higher than the revenue of reducing 100% curtailment. There is a trade-off between increasing the capacity of wind and solar PV to provide more generation and increasing the export capacity. This also impacts space usage at sea for multi-use.



The duration curve figure shows the hourly generation profiles of the wind (green) and the combination with different technologies (other colors).
Each hourly generation profile time series, of a full year (2017) is sorted from lowest to highest hourly generation and plotted to show the correlation between the hourly generation and its occurrence throughout the year.
Plotting this time series yields the number of hours in the year where the production of the considered asset is above (towards right)/below (towards left) the corresponding hourly generation

For a more detailed explanation on these figures, please refer to Annex 1.

Detailed description of Activity 4 can be found in the main report.

Summary

Recommendations

- To have a representation of the entire Dutch North Sea and to draw conclusions of any temporal correlation pattern between the solar and wind, additional sites spread over the area should be considered in the analysis and at least 30 years period to capture climate variability
- An investigation of the benefits of combining offshore wind with storage and/or conversion should be considered to value flexibility as a service, increasing baseload generation and reduction of curtailment.
- The optimal export cable capacity, found to maximize benefits in Activity 4 of this study, underlined the importance of focusing on utilization rate of the export infrastructure over installed capacity. With future connection capacity getting more limited, optimization of the utilization rate should play a key role.
- More detailed calculations of the LCOE values of the individual and combined technologies should be performed, such as dynamic scaling due to decreasing AEP from curtailment, component level costing and the inclusion of synergies in combined cases.
- Investigation of the mutual interaction between the considered technologies, especially offshore wind and offshore solar, is needed to better understand advantages and drawbacks of their combinations. In particular, the interaction from solar PV on the wind resource and shadowing from wind farms (static and dynamic) on offshore PV should further studied

A pragmatic approach has been devised to address the questions from TKI Wind op Zee and RVO in a cost-effective study. Some key findings have been identified that can be used with confidence and are relevant for the Dutch part of the North Sea including resource data and technology, approach to the generation duration curves and NPV calculation, and infrastructure analysis are based on robust assumptions. There are also critical considerations on the assumptions for this study which need to be understood before drawing conclusions.

For a more detailed explanation of the methodology and findings please read the full report below.

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Introduction

Background and research questions

One of the forms of multi-use is to include other renewable electricity generation technologies such as floating solar energy within the wind farm area and sharing the electrical infrastructure and grid connection. The generation profiles of offshore renewable energy technologies differ from the generation profile of offshore wind. The combination of these different profiles may bring benefits of higher utilization of the electrical infrastructure, and a more constant generation profile of the combined technologies. However, there can also be negative impact due to curtailment in periods where the combined production exceeds the nominal capacity of the grid connection. The costs associated with certain technologies may be another challenge for deployment.

This study aims to identify whether the combination of offshore wind farms with floating solar energy in different forms and with shared infrastructure, can bring benefits to the system. It may provide more stable and higher baseload power supply, or negative impact - due to curtailment in periods exceeding the capacity of the grid connection with higher associated costs.

Using realistic and measured time series of wind speed and solar irradiation driving renewable electricity production at a representative location, the following activities are described:

1. Offshore generation profiles for wind energy and floating solar for the Dutch economic zone of the North Sea.
2. Impact on the business case of combining offshore wind and floating solar energy technology.
3. Impact of combining offshore wind energy and floating solar energy technology on the balancing costs of the grid
4. Impact of combining offshore wind energy and floating energy technology on the required optimal capacity of the TenneT infrastructure.

- # Activity 1

Offshore Generation profiles wind and floating solar

Analysis of generation profiles for multi-use offshore wind farms by TNO June 2022

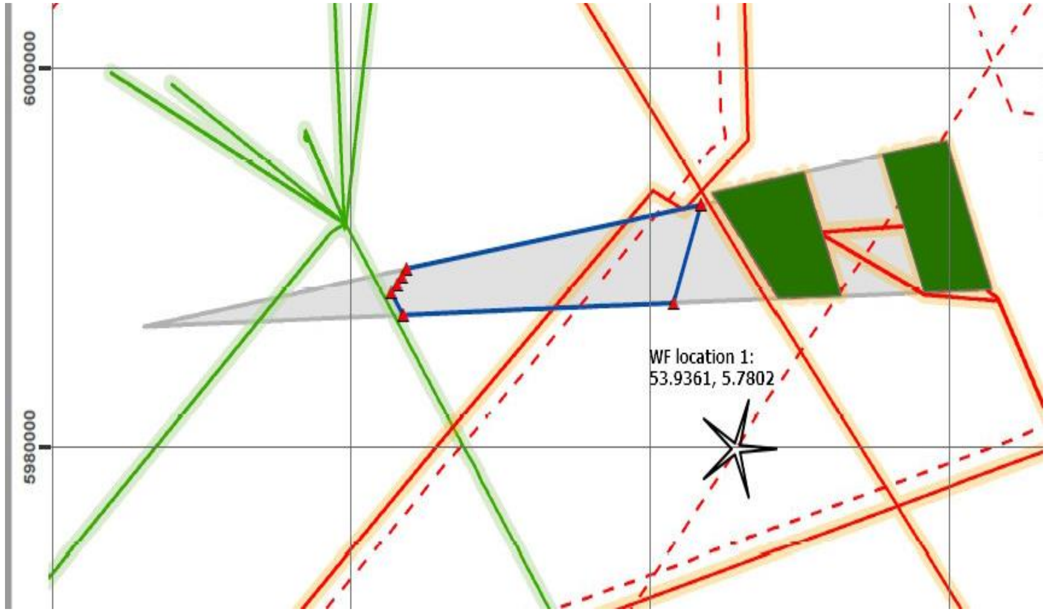
Source: https://www.topsectorenergie.nl/en/spotlight/lower-uncertainties-north-sea-offshore-wind-energy-accurate-wind-information

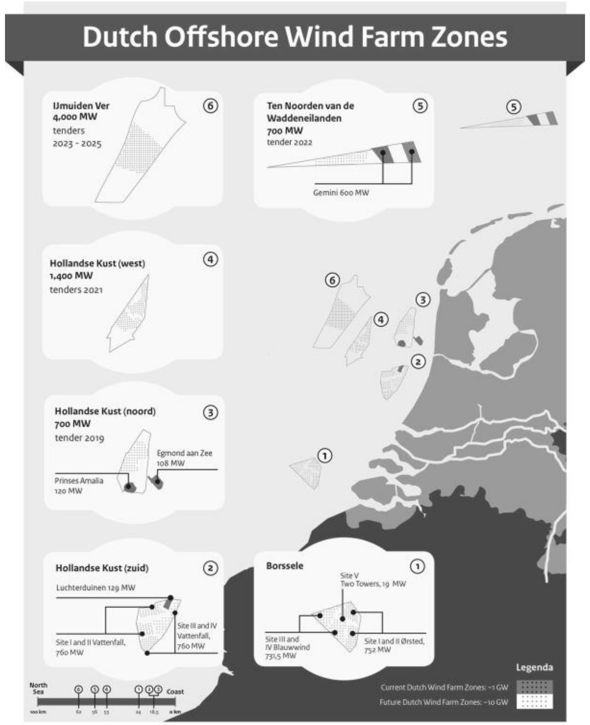
1. Offshore Generation profiles wind and solar

Assumptions: location

The results of this activity are the i) generation profiles for offshore wind energy and offshore solar energy for the Dutch economic zone of the North Sea and ii) the temporal complementarity between the generation sources, analysing their correlation of inter- and intra- annual variability.

The location selected considers a hypothetical offshore wind farm of a size of 1 GW and an associated grid connection of 1 GW just south of the Ten Noorden van de Wadden (TNvdW) wind farm, next to the Gemini wind farm (full green area). This location is selected due to its proximity to the upcoming TNvdW wind farm, being representative for the expected conditions for existing and future wind farms in the Dutch Exclusive Economic Zone.





Source: https://english.rvo.nl/sites/default/files/2020/07/Dutch-Offshore-Wind-Farm-Zones-VJuly2020.pdf

1. Offshore Generation profiles wind and solar

Assumptions: resource datasets and technology

Met-ocean data selected consists of the 10 most recent years available from 2008 to 2017.

The variables selected are the wind speed and direction at hub height 155m height at 10 minutes-based frequency, solar radiation at sea surface at hourly frequency.

Data sources were from the Dutch Offshore Wind Atlas (DOWA), KNMI data platform of the Royal Netherlands Meteorological Institute (KNMI) and the met-ocean data portal from Danish Hydrometeorological Institute (DHI).

The conversion from the met-ocean data into power generation profiles is carried out by using TNO models and power curves based on specific technologies relevant to the time period.

1. Offshore Generation profiles wind and solar

Assumptions: Resource datasets and technology

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Technology	Configuration selected Representative for future (beyond 2030)	Methodology
Offshore wind	Virtual 1 GW wind farm (6 MW/km^2 power density), consisting of 15 MW wind turbine with a rotor diameter of 250 m. Rotor power density = 305 W/m^2. The hub height is 30 m+ D_{rotor}/2 = 155 m hub	The wind resources are based on DOWA (KNMI) wind atlas, determined for a location close to the Ten Noorden van de Wadden wind farm zone. The wind data is an hourly time series for 10 years, 2008 – 2017. The turbine characteristics, i.e. power and thrust curve, are determined using TNO's Blade Optimisation Tool (BOT). The wake losses are predicted using TNO's wind farm yield analysis model, FarmFlow. The losses between the wind turbines and the substation at sea are included in the time series.
Offshore solar	Floating solar farm aligned with the time series of the wind farm, for the same location. TNO's BIGEYE model is used to simulate a single Sun power solar panel with an area of 1.6307 m^2 and 336.05 W peak power (standard test conditions).	Irradiance data, ambient temperature, wind speed at 1.5m height, PV orientation and thermal properties are used to model PV plant performance. The irradiance data is obtained from the nearby KNMI station at Hoorn, Terschelling, while the ambient temperature and wind speed (at 10m above sea level) are obtained from DOWA. The temperature obtained from DOWA is converted to a height of 1.5m through linear extrapolation, while the wind speed is converted to the same height using a logarithmic fit of the data for a height of 10, 20 and 40 m. The single panel performance of the BIGEYE model is converted to plant level using an assumed plant efficiency of 0.9.

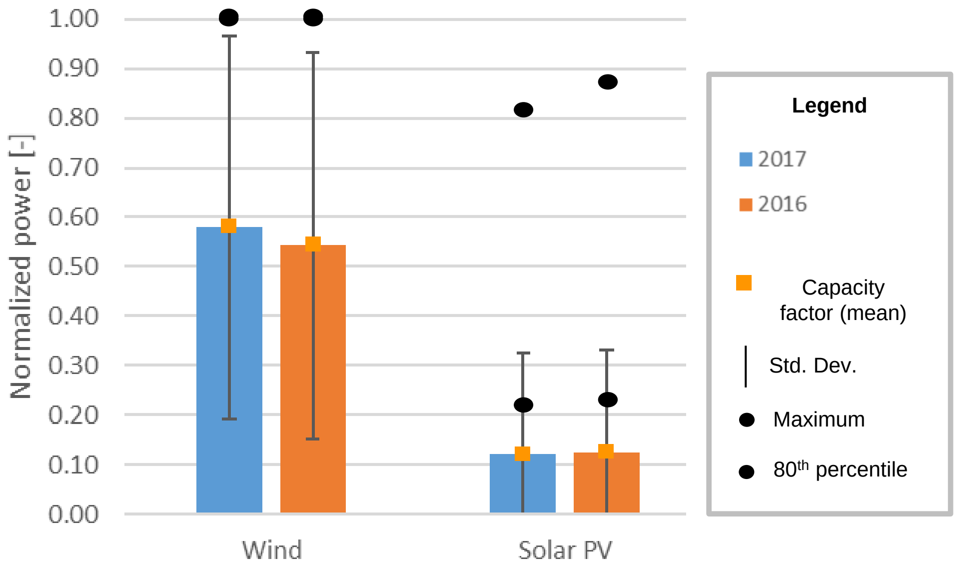
1. Offshore Generation profiles wind and solar

Results

Generation profiles of offshore renewable generation profiles

- Basic descriptive statistics for 2008-2017 of normalized generation profiles for each technology show the interannual variability. 2016 and 2017 are selected for further analysis since the differences are highest with respect to the 10-year average, mainly for wind and solar (2016: 6.43% and 1.33%, 2017: 0.31% and 0.57%), and these being the most recent years.

Box plot of annual capacity factor for each technology



The boxplots in this figure show a compact statistical overview of the wind and solar.

This is visualized through the capacity factor (mean), the standard deviation, the maximum value throughout the year, and the 80th percentile.

For a more detailed explanation, please refer to Annex 1.

Year	Wind [m/s]	Solar [W/m²]
2008-2017	10.5	125.2
Year	Deviations	
2008	5.71%	0.90%
2009	0.08%	4.19%
2010	7.74%	1.00%
2011	3.52%	0.89%
2012	2.29%	2.85%
2013	1.77%	0.40%
2014	1.76%	0.79%
2015	2.90%	0.08%
2016	6.43%	1.33%
2017	0.31%	0.57%

Capacity factor statistics	Wind		Solar PV	
Year selected	'16	'17	'16	'17
20th percentile of power	0.10	0.12	0	0
Average power	0.54	0.58	0.11	0.11
80th percentile of power	1.00	1.00	0.22	0.21
Maximum power	1	1	0.87	0.81

1. Offshore Generation profiles wind and solar
Results

Complementarity of the offshore renewable generation profiles

- The correlation of hourly generation profiles on different temporal scales is performed. Highest correlated values are closer to 1. Positive correlated values indicates that both generation profiles increase and decrease at the same moment, while negative means the opposite. A negative correlation, where wind power increases while the other technology decreases and vice versa, is preferable in order to reduce curtailment and better approximate baseload generation. With positive correlation, the total generation increases more pronounced in the peaks and off-peaks, leading to a larger amount of curtailment of the total generation.
- Wind and solar power are negatively correlated annually (-0.14 to -0.21). The negative correlation is observed during short-periods of several consecutive days. Detailed temporal correlations are included in Annex 1.

- Activity 2

Impact on the business case of combined technologies

Source: https://www.reuters.com/business/energy/tennet-proposes-speeding-up-german-north-sea-offshore-wind-links-2021-10-29/

2. Impact on the business case of combined technologies
Approach – Net present value

To build the business cases, the reference case of 1 GW offshore wind is combined with offshore solar varying capacities:

- The considered installed capacities for solar are in a range from 50 MW to 1000 MW.

The impact on each combined business case is given by combined Net Present Value (NPV). It is calculated by multiplying the hourly profiles of the aggregated generation and the electricity price; subtracting the Levelized Cost of Electricity (LCOE) of the respective components of the combined system. The NPV of each business case is calculated for three scenarios: 2020, 2030 and 2050*.

$$\mathbf{NPV_{combined\ business\ case\ X} = Revenues - Costs = [Aggregated\ Generation\ profiles_{combined\ business\ case\ X}] * [\ Price\ electricity_{scenario\ selected} - LCOE_{aggregated}\ ]}$$

Where the aggregated Generation profiles $_{combined\ business\ case\ X}$ >1 GW will be subtracted as curtailed since the capacity grid assumed is considered 1GW.

2. Impact on the business case of combined technologies

Approach – Net present value

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For the three scenarios selected for 2020, 2030 and 2050, electricity prices are modelled representing as best as possible the situation based on data availability. For the scenario 2020, electricity prices represent 2017 since they must be correlated with the generation profiles. The most recent year of generation profiles is 2017, since they are derived from the met-ocean available data. During this time frame (2017-2020), wind farms were still subsidized, so that prices follow Borssele 1 & 2 wind farms (bottom table). The Hollandse Kust wind farms, commissioned in 2022 and thereafter, are operated without subsidy, so that for the 2030 and 2050 scenarios, all technologies are assumed to be subsidy-free.

Scenario selected	Average price [€/MWh]
2020	ENTSOE 2017, no subsidies 39.3
2020	ENTSOE 2017, subsidized 72.5
2030	73.5
2050	100.6

Price [€/MWh]	
Strike price	72.5
Floor price	29
Subsidy cap	43.5

** Since the NPV calculation is annual for these years, these values are not discounted with inflation. Furthermore, all calculated values are expressed in prices of selected timeframe.*

2. Impact on the business case of combined technologies

Approach - Costs

The calculation of the NPV uses LCOE values for the 2020, 2030 and 2050 scenario, based on literature (table left). The LCOE values are displayed in the tables on the right, showing the base case where the export cable not included in the LCOE of technologies other than Wind (table top), and a case where the export cable cost is included in the LCOE of solar technology (table bottom). The export cable cost consists of the cost for installation of the offshore substation, the equipment and installation cost of the cable from the substation to shore.

The costs of the export cable falls on the wind farm and is included in its LCOE, whereas for the solar technology can share this export cable without any additional cost. This assumption is made since by including export cable cost on other technologies will make a barrier to get a positive business case while sharing wind infrastructure with the solar technology, the business cases become profitable faster. Finally, it is assumed that in these combined projects, the solar technology will have a similar lifetime to the offshore wind.

Technology	Sources LCOE, CAPEX, OPEX 2020, 2030, 2050
Offshore Wind	• Pathways to potential cost reductions for offshore wind energy (TNO, Blix Consultancy for TKI Wind, 2020)
Floating solar	• Technology factsheet solar PV, floating >1 MWp, oriented East/West (TNO, 2021)

LCOE [€/MWh]	2020	2030	2050
Wind (incl. export cable)	55.5*	42.2	30.2
Solar PV (excl. export)	87.4	60.0	31.4

LCOE [€/MWh]	2020	2030	2050
Wind (+export)	55.5	42.2	30.2
Solar PV (+export)	138	101	68

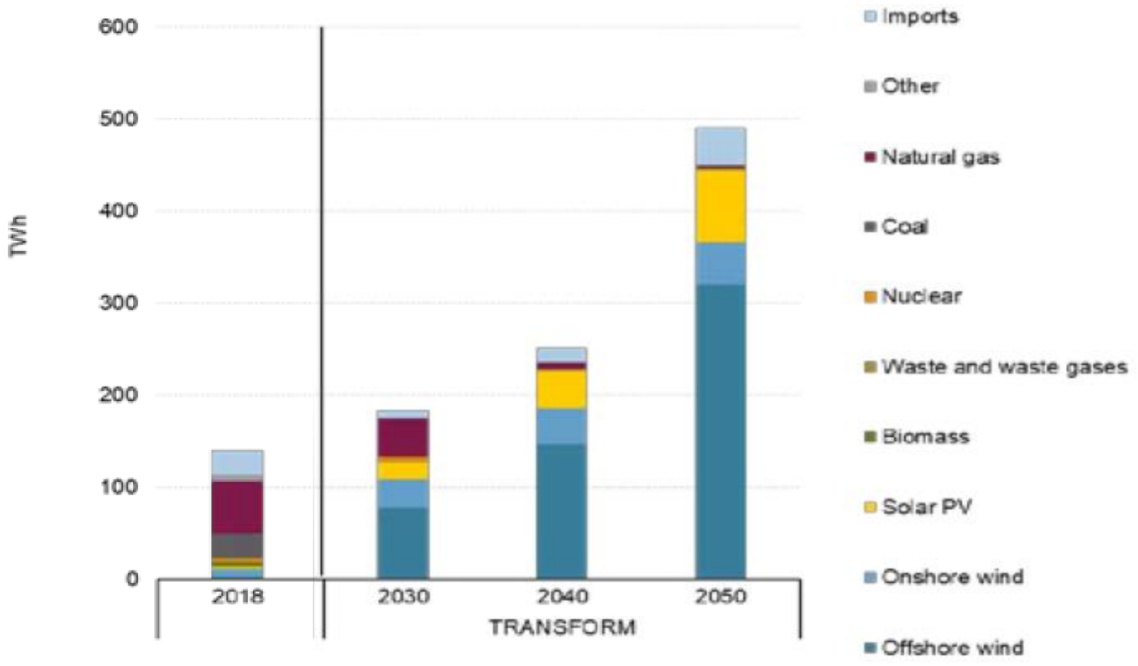
- *Extrapolating the Wind LCOE back to 2017, based on polynomial fit, results in € 60.4/MWh. This extrapolation does not influence the results of the impact on the business cases.*
- *Additional references for global the LCOE figures can be found in IRENA (2021) offshore renewables*

2. Impact on the business case of combined technologies

Approach - Electricity prices and scenarios

The range of electricity prices considered are based on selected 2020, 2030 and 2050 scenario assumptions, following a Dutch decarbonization pathway with the interim target for 2030 (National Energy and Climate Plan, Climate Agreement). The scenarios selected will be based on the TNO Dutch decarbonization pathways to reach up to 35-75 GW RES by 2050, so-called ADAPT and TRANSFORM scenarios, which has been discussed and used as reference by PBL, for several integration studies.

	ADAPT	TRANSFORM
Landscape	• Netherlands and EU will meet 2030 and 2050 GHG reduction targets. • Society values current living standards. • EU countries have their own policies in achieving GHG reduction. • Industrial production and economic structure remain basically the same.	• Netherlands and EU will meet 2030 and 2050 GHG reduction targets. • Strong environmental awareness and sense of urgency in society. • EU and Netherlands want to become innovative power house. • Individual and collective action by civilians.
Regime	• National and local government take the lead. • Adapting and optimizing the energy system and industrial processes. • Keep options open and structural change post 2020. • Fossil fuels are expected to be utilized in combination with carbon capture and storage (CCS) to abate CO_2 emissions. • Imports of biomass and biofuels.	• Government has a stimulating and enabling role. • Ambitious transformation of energy system, replacement of energy intensive industry, resulting in lower industrial production and energy use, increase of service sector. • Reduction of other GHG intensive activities (cattle, international travel, etc.). • No carbon capture and storage (CCS), and limited biomass use.



Source: Scenarios for a climate-neutral energy system (TNO 2020)

2. Impact on the business case of combined technologies

Approach - Electricity prices and scenarios

The assumptions include behavioural changes and deployment of new innovative technologies leading to a clean, energy-efficient economy. The development of population growth, GDP, fossil and renewable fuel costs and technology costs are kept the same. Scenarios have been calculated with differences in the development of energy demand and the availability of a number of technology options. This has resulted in projections for the years 2030 and 2050, expressed in technical and economic parameters, the required inputs to estimate the range of electricity prices. The prices have been calculated by modelling dispatch in the day-ahead power market, considering main influencing drivers under different sensitivities: CO2 ETS costs, flexibility options in the form of conversion and storage option capacities and demand fluctuation profiles.

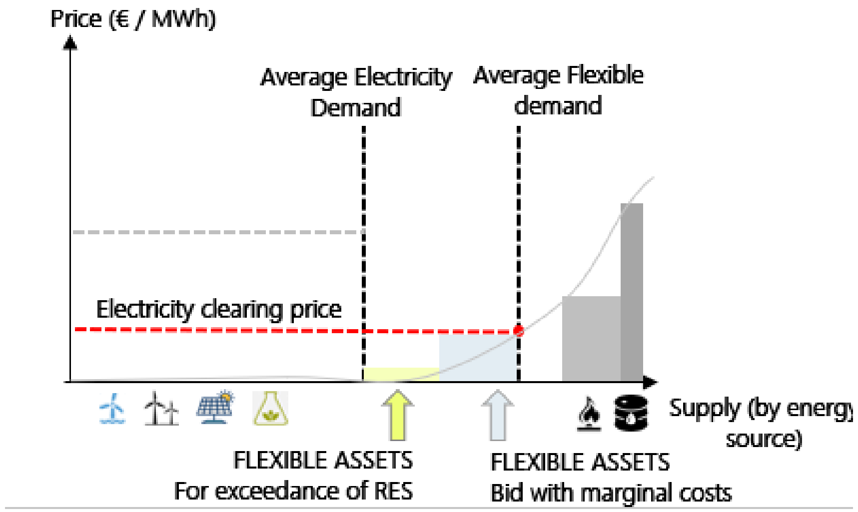
	Today	(KEV, 2020) 2030	Wind - Solar competition	From importer To exporter	Higher CO_2 prices	Higher flexible demand	Traded volumes in SPOT market	Accelerated RES integration	Decarbonized system
SCENARIOS Main assumptions	**2019**	**BASELINE 2030**	**Solar PV Grid**	**Net exports**	**EU-ETS CO_2**	**FLEXIBLE DEMAND**	**MARKET SETUP**	**TRANSFORM 2030**	**TRANSFORM 2050**
Total elec. demand (TWh)	112	137	137	137	137	137	*137*	165	270
Total flex.* demand (TWh)	0	30	30	30	30	0; 30; 40	*30*	44	315
Net exports (% elec. demand)	-11%	+11%	+11%	-5%; +11%; 20%	+11%	+11%	*+11%*	+20%	+20%
Solar PV (GW)	3.9	20	10 ; 15; 20	20	20	20	*20*	39	127
Onshore Wind (GW)	3.6	6.9	6.9	6.9	6.9	6.9	*6.9*	8	12
Offshore Wind (GW)	0.9	11.5	11.5	11.5	11.5	11.5	*11.5*	14	60
CCGT Natural gas (GW)		17.8	17.8	17.8	17.8	17.8	*17.8*	17.8	12.8
ETS costs (€/Tn CO_2)	20	43	43	43	28; 43; 75; 100	43	*43*	80	400
EPEX (%)	25	100	100	100	100	100	*20; 30; 40*	100	100
RES cost (€/ MWh)	0	0; 1.6	0; 1.6	0; 1.6	0; 1.6	0; 1.6	*0; 1.6*	0; 1.6 ; 1.9	0; 1,6 ;1.9

Source: Scenarios for a climate-neutral energy system (TNO 2020)

2. Impact on the business case of combined technologies

Approach - Electricity prices and scenarios

The Dutch electricity market is modelled using the EYE (ElectricitY market price Evolution simulator) model. The EYE model is an electricity system simulator which estimates electricity prices given certain scenario inputs such as technology specifications and costs, commodity prices, expected demand etc) and bidding strategies. The order of the technologies follow the merit order: must run assets enter first in the bid, and are located on the left side of the price curve. Next, near or zero price technologies enter due to RES supply. Conventional fossil-fuelled assets and biomass with higher operating costs are on the other end of the curve. Generally, flexible assets are included in the middle range of the price duration curve and are characterized by high prices. In the EYE model if flexible assets are not completely fed by RES, their operating costs are high due to being fed by conventional energy sources.



Sources:
1. Krishna-Swamy S., Gonzalez-Aparicio I, Stralen J., Bulder B. Developing a long-lasting offshore wind business case in the energy transition by 2050. Journal of Physics. WindEurope Electric City 2021. Accepted for publications – Q1 2022
2. Gonzalez-Aparicio I, Krishna-Swamy S., Stralen J., Bulder B. Developing a long-lasting offshore wind business case in the energy transition by 2050. TNO 2020 R12096

- # Activity 2.1

Offshore wind and floating solar PV

Source: https://www.technischweekblad.nl/nieuws/drijvende-zonnepanelen

2. Impact on the business case of combined technologies

2.1 - Results: offshore wind and floating solar pv

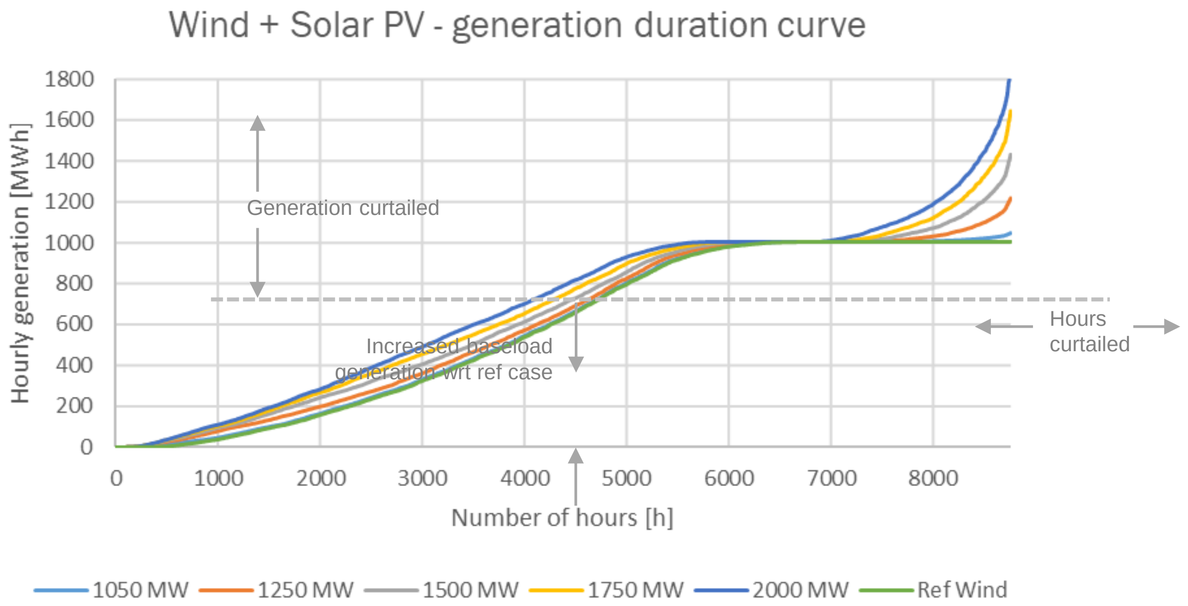
Total combined generation

The hourly generation duration curve in 2017 of the combined technologies shows that the addition of solar PV will increase the total generation for a total of 5500 hours, while curtailment is required for approximately 1700 hours. The generation above 1000 MW is curtailed since the export cable capacity is unchanged and assumed to be 1 GW.

In this case, due to the higher average LCOE of the solar PV production in all cases, it is assumed that all curtailed energy is from solar PV.

As can be seen from the descriptive statistics on the generation (table), the addition of solar PV to a 1 GW wind farm leads to curtailment of up to 6.3% for the 1 GW solar case. At the same time, the utilization of the (1 GW) export cable is increased from 58% to 65%, with an additional annual generation of 644 GWh exported. While the total generation to the grid of the reference case (only wind) is 5102 GWh, the total generation when adding 1 GW of floating solar is 6168 GWh.

For a more detailed explanation on these figures, please refer to Annex 1.



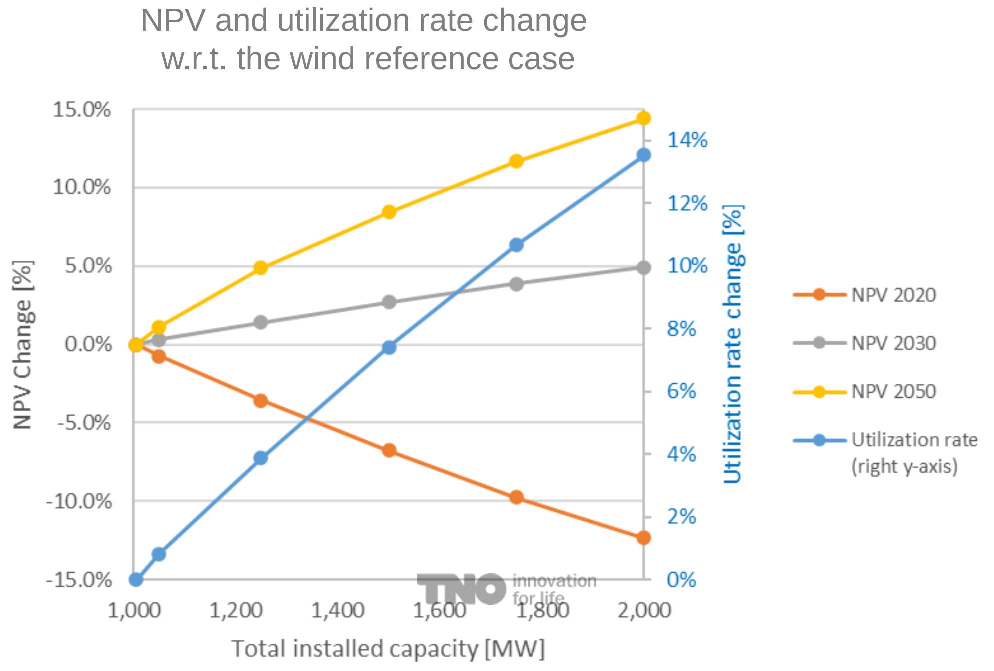
Statistics	50 MW	250 MW	500 MW	750 MW	1000 MW	Ref. Wind
Total installed capacity [MW]	1050	1250	1500	1750	2000	1000
Total Peak generation [MW]	1048	1218	1431	1644	1858	1000
Total Energy Production [GWh]	5156	5369	5635	5901	6168	5102
Solar Production [GWh]	53	266	533	799	1065	-
Total Energy curtailed [%]	0.23%	1.36%	2.91%	4.55%	6.26%	0%
Total generation to grid [GWh]	+39	+184	+350	+504	+644	5102
Grid connection utilization rate [%]	58.40%	60.04%	61.94%	63.68%	65.27%	57.96%

2.1 - Results: Offshore wind and floating solar pv

Total combined generation

Combining floating solar with wind generation, the NPV decreased in the scenario selected for 2020 but starts increasing with respect to the reference case from the 2030 scenario onwards (figure, left axis, and table for absolute values). This is caused by the higher solar LCOE of today and the steep downward trend of the LCOE in the 2030 and 2050 scenarios. The utilization rate of the export cable (figure, right axis) increases over 12% for an installed capacity of 2 GW.

Note that LCOE for solar PV considered in this calculation (87.5, 60 and 31.4 €/MWh for 2020, 2030 and 2050 scenarios, respectively) does not include cost of the export cable infrastructure. If included, this would increase the LCOE of solar by 50.3, 40.7, and 36.6 €/MWh for 2020, 2030, and 2050 scenarios, respectively. This in turn would yield a negative business case for most of the considered cases, with a positive business case only under the 2050 scenario.



For a more detailed explanation on this figure, please refer to Annex 1.

Statistics	50 MW	250 MW	500 MW	750 MW	1000 MW	Ref. Wind
Total NPV 2020 – Solar [M€]	-0.6	-3.0	-5.8	-8.3	-10.5	**85.1**
Total NPV 2030 – Solar [M€]	+0.5	+2.3	+4.3	+6.2	+7.9	**160.7**
Total NPV 2050 – Solar [M€]	+4.5	+19.6	+34.0	+47.0	+58.2	**403.4**

2. Impact on the business case of combined technologies

2.1 - Conclusions: Offshore wind and floating solar pv

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Combining offshore wind and floating solar, there is a positive impact on the business case after 2030, under specific conditions

- The total aggregated generation of wind and solar is 6168 GWh while the wind generation is 5102 GWh, increasing solar by 644 GWh (12.6%) in the generation exported to the grid, in the case of 1 GW of installed solar PV capacity together with 1 GW of wind. Despite the 1 GW limitation in export capacity, the curtailment of solar PV is relatively limited, with all installed capacities of solar PV curtailing less than 50% of their total generation. Finally, the export cable utilization rate increase of 12% (from 58% to 65%) will lead to reduced variability of the (combined) generation profile, and more closely approach a situation of full baseload generation.
- Comparing the combined case providing 6168 GWh with adding wind turbines to the 1 GW of offshore wind farm to achieve the same increase in utilization rate of the export cable (1 GW). A total of 29 additional wind turbines would be required to reach an export cable utilization of 65.8%, yielding a total installed wind capacity of 1.44 GW. At the same time, this configuration would lead to a total curtailment of 20.7% of the aggregated generation while in the combined case the curtailment is 6.3%. Using 2050 prices, the value of lost generation for this all-wind case (1.44GW) would be approximately 174 M€, while the curtailed energy in the solar case has a value of approximately 80 M€. This makes the combined business case of wind and solar more attractive.
- The positive impact on the combined case becomes clear under the 2030 and 2050 assumptions. An increase in the calculated NPV shows that there is a positive business case for the combined technologies. The positive NPV in these cases is driven by the reduction in LCOE and higher market prices for those years. In 2020, the estimations show a negative impact on the combined business with a negative trend for the NPV compared to the reference case of wind.

2. Impact on the business case of combined technologies

Conclusions: Offshore wind and floating solar pv

There are critical points to consider on the ‘positive’ combined business case

Production

- In the floating solar PV generation profiles efficiencies are associated with lakes since the technology is not yet in operation at sea. Furthermore, the effect of the losses of connecting solar with a wind farm such as the dynamic and static shadowing effects, roughness length modification of solar panels impacting on wind energy production, etc, are not considered. Those aspects may lead to additional production losses, which will impact the total generation and thus, the revenues.

Infrastructure

- The floating PV technology shows a positive business case only in combination with offshore wind energy, not alone. This is mainly due to the infrastructure and costs associated (offshore substation, export cable equipment and installation) are shared with the offshore wind. And the wind LCOE includes all the costs of the export cable, not the solar LCOE.

Technology, costs and revenues

- The CAPEX and OPEX and consequently, the LCOE are the main drivers of the profitability. Therefore, the downward future LCOE trend plays a crucial role to maintain a positive business case.
- The revenues are based on estimated future electricity prices, which tend to increase beyond 2030 due to the costs of flexibility. If the electricity market future behaviour changes by dropping electricity prices, the business case will be negatively affected.

Activity 3

Impact of business cases on grid balancing costs

Source: https://iro.nl/nl/nieuws-en-pers/deme-offshore-awarded-transport-installation-contract-for-hollandse-kust-noord-and-west-alpha-offshore-substations/

3. Impact of business cases on grid balancing costs

Approach and assumptions

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This activity studies the impact of combining offshore wind energy and other offshore renewable energy technologies on the balancing costs of the grid. A positive impact is given by the case that reduces the variability of the supplied generation, and more closely approximates baseload generation. An illustrative case is shown in the figure below, where the best-combined business cases (BC) found in previous sections are shown to add to the reference wind production at different moments in time.

The positive imbalance costs considered are at a 15-minute frequency (€/MWh) for 2017 (ENTSO-E transparency platform). It is assumed that the reference case of the only wind farm is the perfect foresight. The positive imbalance costs are added to the selected combined business cases when the generation is increased each hour with respect to the reference case. The resulting positive deviation of the generation (in MWh) and valuation per time step (in €/MWh) is performed for two best-combined business cases:

- 1 GW offshore wind connected with 500 MW floating solar PV
- 1GW offshore wind connected with 1 GW floating solar PV

The grid connection assumed in this analysis is 1 GW, all generation in excess for the combined business cases is curtailed.

3. Impact of business cases on grid balancing costs

Results

The calculation of the imbalance cost for the 500 MW and 1 GW solar PV cases estimates a total reduction by 11.7 M€ and 21.2 M€, respectively. This result means the reduction in imbalance due to the additional generation to the grid of 350 GWh for the 500 MW case and 644 GWh for the 1 GW case, is valued at an average of 33.4 and 32.9 €/MWh, respectively. Balancing cost for the reference wind case is equal to zero, since perfect foresight is assumed. Including the calculated imbalance cost in the NPV would yield a positive case for both the 500 MW and 1 GW capacities at 91 and 95.8 M€, compared to an NPV of 85.1 M€ for the reference wind case.

Business cases	Total NPV 2020	Total NPV 2020 including positive imbalance
Reference case wind	85.1	85.1
Solar – 500 MW	79.3	91
Solar – 1 GW	74.6	95.8

Imbalance impact (€)	500 MW Solar	1 GW Solar
Total [M€]	11.7	21.2
Average [k€]	1.3	2.4
Normalized [€/MWh]	33.4	32.9

3. Impact of business cases on grid balancing costs

Conclusions

- The addition of solar PV to the wind-only generation will lead to an increase in utilization of the export cable and reduction in variability of generation, since the combined generation will more closely approach baseload generation. Imbalance could be further reduced through inclusion of storage options, which can also reduce the amount of curtailment.
- To arrive at a better estimation of the actual imbalance of the combined technologies, this analysis would have to be extended to include forecast of the expected generation. This could then be compared with the realized generation in order to estimate the imbalance. In addition, if this comparison is performed for a longer period, it would yield statistics on the average forecast for each considered technology. This information could then be used to better estimate the actual imbalance from each technology in the combined cases.
- Note that the calculation performed in this activity assumes that there is no prediction of the additional solar PV generation added in this combined case. Therefore, the offshore wind is the only generation that is forecast and will bid into the electricity market, while the solar PV generation is not predicted, and will therefore be regarded as an imbalance.

Activity 4

Impact of business cases on optimal capacity of infrastructure

Source: https://www.tennet.eu/nl/tinyurl-storage/nieuws/tennet-sluit-windparken-op-nederlandse-noordzee-aan-met-verbindingen-met-hoogste-capaciteit-ter-were/

4. Impact of business cases on optimal capacity of infrastructure
Approach

The impact of combining offshore wind and floating solar energy on the required optimal capacity of the export infrastructure is considered. The goal of this activity is the estimation of the required curtailment and resulting NPV of the combined case in the 2050 scenario, for different export infrastructure capacity, accounting for the cost associated with expansion of this infrastructure.

To this end, two cases for the export cable capacity are considered: a case with a total export capacity of 1.4 GW, and one with 1.8 GW. These increase cable sizes are selected based on a typical substation size of 700 MW[1], leading to a 400 MW step from 1 GW, with an additional 400 MW step to reach 1.8 GW.

For these two cases as well as the reference case, the total amount of curtailment, value of this curtailed energy and new NPV will be calculated for the 2050 scenario. This NPV calculation will use new values for the LCOE, based on the expanded export cable.

[1] https://www.tennet.eu/tinyurl-storage/detail/tennet-and-engie-solutionsiemants-sign-contract-for-offshore-transformer-substation-hollandse-kust/

Assumptions

LCOE of the offshore wind generation is unchanged, with the additional cost of the 0.4 GW or 0.8 GW expansion falling on the solar PV installation, resulting in a higher LCOE (table). It is assumed that this cost is only a CAPEX increase, and there is no increase in OPEX for this expansion.

For calculation of the new LCOE, it is assumed that the AEP of the technologies is static, i.e. it does not take into account the curtailment due to the available export capacity. In reality, curtailing energy would increase the LCOE of the technologies, due to the decrease in AEP.

The additional export capacity is assumed to be installed at the same (unit) cost as the original 1 GW export infrastructure. The technical and legal implications and implementation of such an expansion are not considered in this study.

This analysis only considers the 2050 scenario, since it was shown to yield the highest NPV increase when introducing solar PV (in chapter 3).

LCOE [€/MWh]	2020	2030	2050
Wind	55.5	42.2	30.2
Solar PV (excl. export)	87.4	60.0	31.4
Solar PV (+0.4 GW export)	107.5	76.3	46.1
Solar PV (+0.8 GW export)	127.7	92.6	60.7

4. Impact of business cases on optimal capacity of infrastructure

Results

The table below shows the total curtailment (in GWh and %), frequency and value of the curtailment and the resulting NPV for three different sizes of export cable: 1.4 GW, 1.8 GW, and the reference case of 1 GW. Results indicate that the increase of export cable capacity from 1 GW to 1.4 GW has a positive effect on the overall NPV of the combined case, with the NPV of the 1 GW solar case increasing from 461.5 to 499.3 M€. At the same time, the value of the total amount of curtailed energy reduces from 80 to 17.1 M€. This is mainly because the cost considered in the study to increase the export cable are lower than the revenues obtained by the generation curtailed in the case with 1 GW of export cable.

However, when increasing the export infrastructure further to 1.8 GW, the results are not the same: although the curtailed energy and therefore lost value reduces to (almost) zero in for all capacities of solar, the NPV decreases in comparison to the 1.4 GW case. This indicates that the increased revenue from energy that would otherwise be curtailed no longer outweighs the additional cost of the export infrastructure expansion.

Export cable	Statistics	Solar - 50 MW	Solar - 250 MW	Solar - 500 MW	Solar - 750 MW	Solar - 1000 MW	Reference Wind
-	Total generation [GWh]	5156	5369	5635	5901	6168	5102
1 GW	Curtailment [GWh]	11	68	155	255	375	-
	Share of curtailed energy [%]	0.22%	1.27%	2.75%	4.31%	6.08%	-
	Frequency of curtailment [h]	1130	1364	1516	1670	1855	-
	Value of curtailed energy [M€]	**2.1**	**14.2**	**34.1**	**55.8**	**80.0**	-
	NPV [M€]	**407.9**	**423.0**	**437.4**	**450.4**	**461.5**	403.4
1.4 GW	Curtailment [GWh]	0.0	0.0	0.2	13.4	50.1	-
	Share of curtailed energy [%]	0.00%	0.00%	0.00%	0.23%	0.81%	-
	Frequency of curtailment [h]	0	0	14	151	317	-
	Value of curtailed energy [M€]	**0.0**	**0.0**	**0.0**	**4.4**	**17.1**	-
	NPV [M€]	**408.9**	**431.1**	**458.7**	**482.7**	**499.3**	403.4
1.8 GW	Curtailment [GWh]	0.0	0.0	0.0	0.0	0.4	-
	Share of curtailed energy [%]	0.00%	0.00%	0.00%	0.00%	0.01%	-
	Frequency of curtailment [h]	0	0	0	0	12	-
	Value of curtailed energy [M€]	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	-
	NPV [M€]	**408.1**	**427.2**	**450.9**	**474.7**	**498.5**	403.4

4. Impact of business cases on optimal capacity of infrastructure

Conclusions

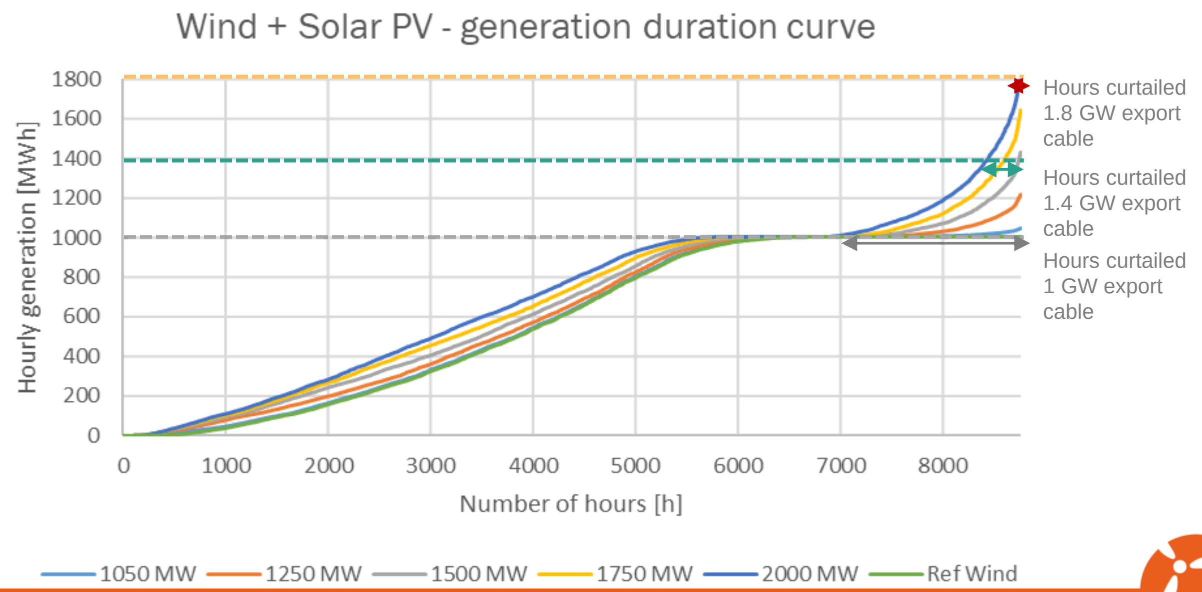
There is a benefit to expanding the export infrastructure up to 1.4 GW to accommodate the additional installed (solar) capacity, in order to allow an additional 325 GWh, valued at 63 M€, of generation to feed into the grid, reducing the share of curtailed energy from 6.1% (375 GWh) to 0.8% (50 GWh). However, this expansion does not necessarily have to match the rated capacity of the total installed generation in order to maximize its benefits, since an expansion to 1.8 GW will only allow an additional 50 GWh, valued at 17 m€, to be exported to the grid.

These benefits depend strongly on the decrease in solar LCOE towards 2050, as well as the higher market prices in the 2050 scenario compared to the 2020 scenario. Since the CAPEX involved in the expansion of the export infrastructure is assumed to be mostly constant throughout these years, the decrease in LCOE is the main driver for this case. Furthermore, it is assumed that the expansion of the electrical infrastructure incurs no additional OPEX cost, and there is only a CAPEX increase for the expansion of the export cable capacity.

The duration curve presented here shows the impact of the expansion of the export infrastructure on the generation profile of the combined asset.

The dashed lines in this graphic show the limitations of the available infrastructure, above which all the additional generation is curtailed. Thereby, the number of hours of curtailment in a year are visualized.

For a more detailed explanation on duration curves, please refer to Annex 1.



Recommendations

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- To have a representation of the entire Dutch North Sea and to draw conclusions of any temporal correlation pattern between the solar and wind, additional sites spread over the area should be considered in the analysis.
- An investigation of the benefits of combining offshore wind with storage and/or conversion should be considered to value flexibility as a service, increasing baseload generation and reduction of curtailment.
- The optimal export cable capacity, found to maximize benefits in Activity 4 of this study, underlined the importance of focusing on utilization rate of the export infrastructure over installed capacity. With future connection capacity getting more limited, optimization of the utilization rate should play a key role.
- More detailed calculations of the LCOE values of the individual and combined technologies should be performed, such as dynamic scaling due to decreasing AEP from curtailment, component level costing and the inclusion of synergies in combined cases.
- Investigation of the mutual interaction between the considered technologies, especially offshore wind and offshore solar, is needed to better understand advantages and drawbacks of their combinations. In particular, the interaction from solar PV on the wind resource and shadowing from wind farms (static and dynamic) on offshore PV should further studied.

A1. Interpretation of graphics

Duration curve graphic

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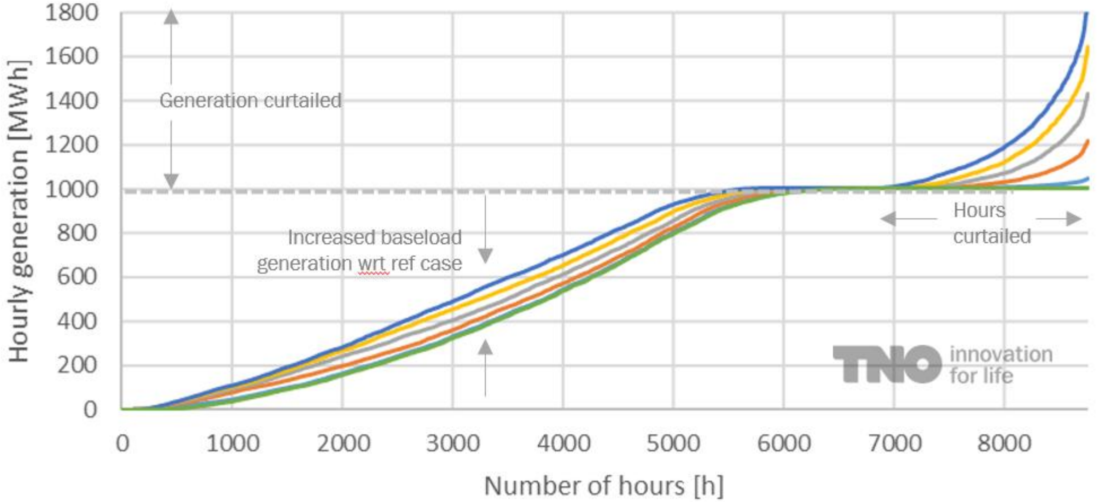
The duration curves presented in this report show the impact of the combination of different technologies on the generation profile of the combined asset.

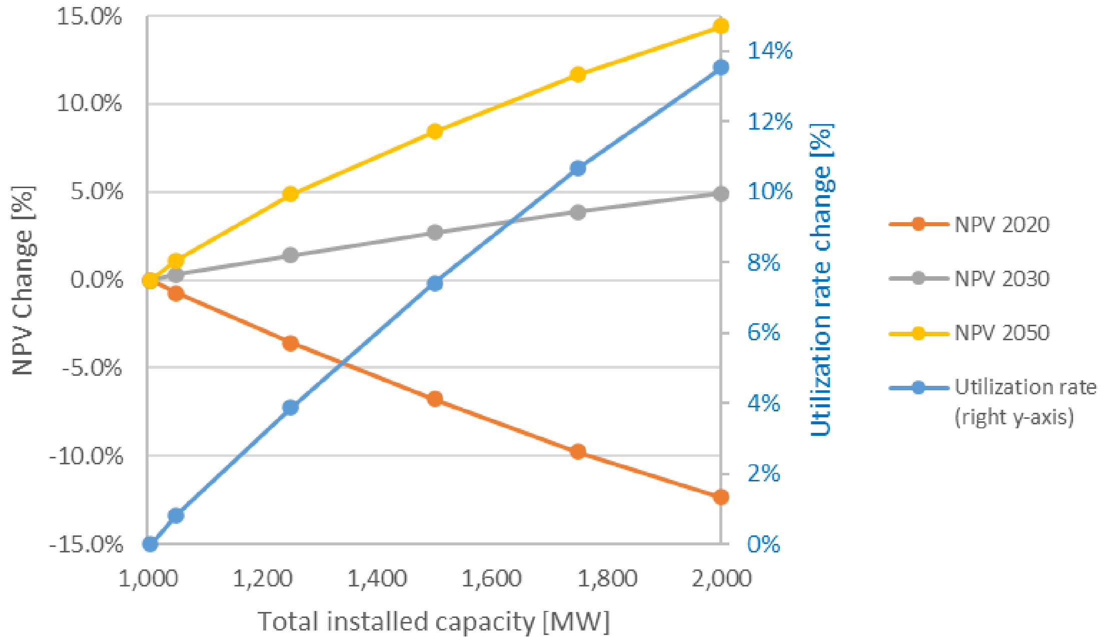
- In order to create this graphic, an hourly time series of a full year of generation for the combined asset is sorted from lowest to highest hourly generation. Plotting this time series yields the number of hours in the year where the production of the considered asset is above (towards right)/below (towards left) the corresponding hourly generation.
- Example: the duration curve below shows that there are ~5500 hours in the year where the hourly production of the combined asset is less than 1 GWh. It can be seen that in these 5500 hours of <1 GWh production, there is on average higher generation when adding solar PV (orange, gray, yellow and blue line), than for the reference wind case (green line). At the same time, the addition of solar PV also introduces >1 GWh generation beyond the 7000 hour mark, which cannot be exported due to the limitation of the export cable (1 GW). Therefore, this generation will be curtailed.



A1. Interpretation of graphics
NPV and utilization rate change

This figure shows the change in NPV and export cable utilization rate due to the combination of different technologies.

- On the left axis, the change in NPV from the reference wind case (installed capacity 1000 MW) is shown for different combined installed capacities. As can be seen from the below example, the change in NPV varies for the scenario considered. Here, the 2020 scenario shows a negative trend in NPV for increasing installed capacity of solar PV, whereas the 2030 and 2050 scenarios show an increase in NPV for additional installed capacity.
- The right y- axis (in blue) shows the increase in utilization of the export cable due to the combined technologies.

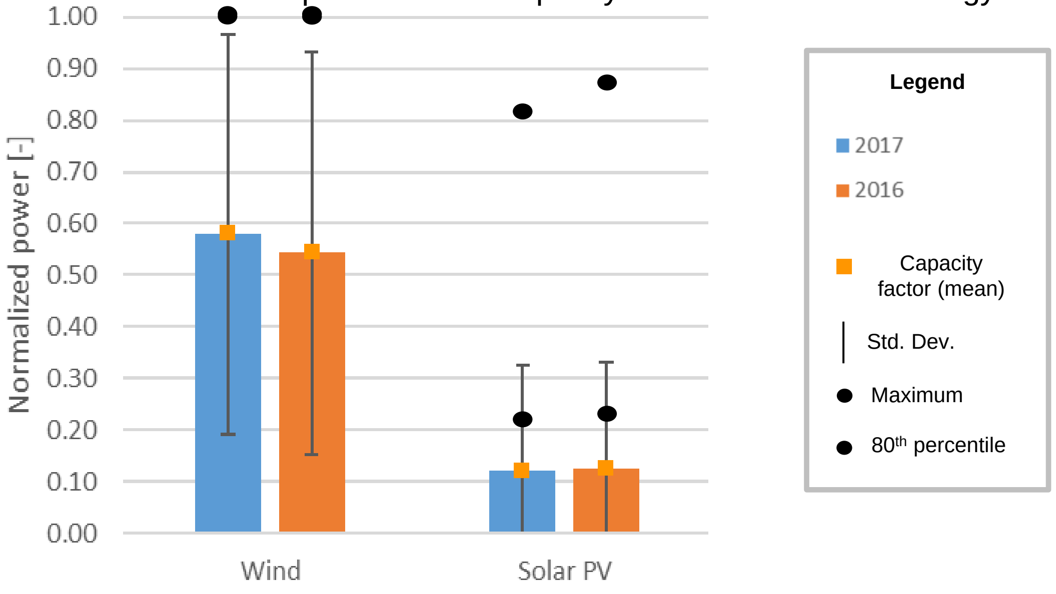


A1. interpretation of graphics
Annual Capacity factor Box plot

The boxplots in this figure show a compact statistical overview of the different considered technology.

- The annual production of the technology is visualized through the capacity factor (mean), the standard deviation from this mean, the maximum value throughout the year, and the 80th percentile.
- The 80th percentile marker captures the bottom 80% of the total annual production values. Therefore, the top 20% production values are captured between it and the maximum value marker.
- Statistics of both the 2016 and 2017 year are displayed, to show variations in the characteristics of the technologies.

Box plot of annual capacity factor for each technology



Annex 2. Additional Results – Correlation Matrices

Complementarity of the offshore renewable generation profiles

- Additional correlation matrix for the 2016-2017 period shows floating solar hourly profiles are negatively correlated with the wind generation (-0.14).

The correlation analysis has been made using scatter plots and correlation matrices (following slides).
Further descriptions of how to read scatter plots and correlation matrices can be found in those links: here and here.

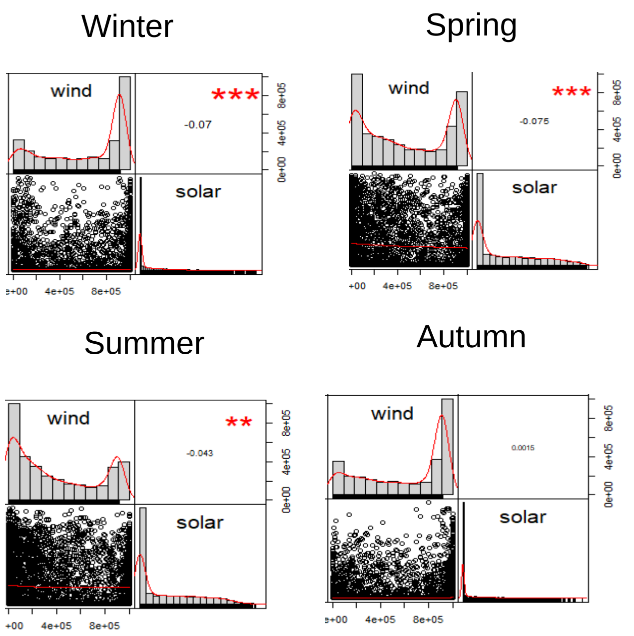
A2. Offshore Generation profiles wind and solar

Annex 2. Additional Results – Correlation Matrices

Complementarity of the offshore renewable generation profiles

The analysis of the correlation on intra annual variability (selecting 2016 and 2017) shows a similar pattern than on the inter annual variability, although in specific seasons and months the correlation between technologies changes:

Wind and solar profiles are not correlated seasonally (<-0.07). The effect found during the years occurred during specific hours, indicating that the complementarity does not follow a seasonal pattern.



A2. Offshore Generation profiles wind and solar

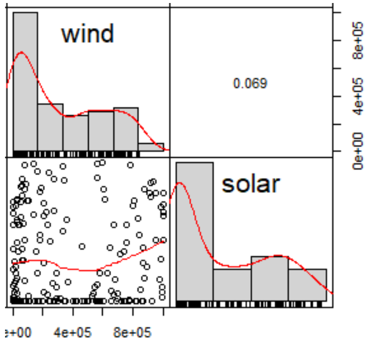
Annex 2. Additional Results – Correlation Matrices

Complementarity of the offshore renewable generation profiles

The monthly analysis (selecting 2016 and 2017) show the same patterns as 2008-2017 period and for each year. For specific months the correlations between technologies are higher than others, as expected due to climatic variability over the year. It should be noted that the highest correlation between wind-solar hourly profiles are in June (-0.13), as in the seasonal analysis, there is no pattern during the year.

Short-term analysis during two random weeks in summer (1^{st}-8^{th}July) and winter (1^{st}-8^{th} January) in 2017 show the same temporal complementarity pattern as the inter-and intra- annual. The wind and solar complementarity show different results, while in summer it is not appreciable, winter week has a -0.12 correlation. That is, the complementarity between wind and solar is rather arbitrary, following a weak seasonal or monthly variability up to -0.20. Once again, it may depend on specific hours where higher correlations can be found.

Summer 2017: 1^{st} – 8^{th} July



Winter 2017: 1^{st} – 8^{th} January