Dimensioning and optimization of multi-source offshore renewable energy parks

Anton B. Schaap, Hinne F. van der Zant, Sarah Kluge, Simon J. Stark

Abstract—**Multi-source offshore renewable energy parks are a promising new development in offshore renewable energy. In these parks, wind, solar and/or wave power is connected to the onshore grid with a shared substation and export cable. With multi-source parks, the capacity factor of the network connection can be raised, reducing the overall network connection costs, while also reducing the grid balancing costs and making more efficient use of available sea space. The importance of adding wave power can be derived from the average price difference of wave power compared to solar and wind. With the DMEC simulation program, hourly prices for the Netherlands electricity market bidding zone for 2030 and 2050 are calculated. With this model a 23% higher wave energy price than wind over the year 2030 and an 11% higher price than wind over the year 2050 is calculated. The results are preliminary since the project is ongoing and the model will be further refined.**

Keywords—**Electricity system simulation, multi-source park design, offshore solar energy, offshore wind energy, tidal current energy, wave energy**

I. Introduction

Multi-source offshore renewable electricity parks consist of wind, solar and/or wave power converters connected to the onshore grid with a shared substation and export cable. By applying more than one renewable energy generation type in a single park, the capacity factor of the network connection can be raised. In this way the overall network connection costs can be reduced, while also reducing the grid balancing costs. More efficient use is made of the available sea space, if floating solar and/or wave power is added in between the wind turbines. There can also be an integrated service system for the wind, solar and/or wave devices in the park. The wave park can serve as a wave barrier for the wind park, reducing the average wave height in the park and expanding the weather window for service operations [1].

Adding wave power and solar power to a wind park is especially valuable when the overlap of the production profiles of wave and solar with the wind production profile is modest and therefore curtailment will be low. There will also be a better business case for wave and solar when the overlap between the solar and wave generation profile and the wind profile will be low. Interesting is especially the average price that wave energy can receive for its production compared to the average price for wind and solar.

The Dutch Marine Energy Center (DMEC) has performed an electricity-price simulation study for the future Dutch offshore wind park Ten Noorden van de Waddeneilanden (TNW), when integrating wave power and solar power in the park. With the rising share of weather dependent renewables in the electricity mix, the electricity price is becoming more and more volatile. Therefore, a design process of a multi-source park should also incorporate a pricing mechanism that can produce hourly electricity prices based on actual wind, solar and wave conditions. Since there is a single electricity pricing zone (bidding zone) in the Netherlands, the electricity price can only be simulated with a model that (at least) considers the whole of the Netherlands (onshore and offshore). Simulating the whole interconnected electricity system of Western Europe, would be better. However, since the interconnection capacity is limited, the influence of electricity prices in the surrounding countries is also limited and can be integrated as a flexible load.

The first multi-source parks are planning installation before the year 2030, like the combination of wind and solar in the CrossWind consortium by Shell and ENECO for Hollandse Kust Noord and the RWE project Hollandse Kust West VII [2]. Since such a multi-source

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A.B Schaap is with Dutch Marine Energy Centre (DMEC), Hellingweg 11 c/d 2583 DZ The Hague The Netherlands (e-mail: anton@dutchmarineenergy.com).

H.F. van der Zant is with Dutch Marine Energy Centre (DMEC), Hellingweg 11 c/d 2583 DZ The Hague The Netherlands (e-mail: hinne@dutchmarineenergy.com).

S. Kluge is with Dutch Marine Energy Centre (DMEC), Hellingweg 11 c/d 2583 DZ The Hague The Netherlands (e-mail: sarah@dutchmarineenergy.com).

S. J. Stark is with Dutch Marine Energy Centre (DMEC), Hellingweg 11 c/d 2583 DZ The Hague The Netherlands (e-mail: simon@dutchmarineenergy.com).

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park will have an expected lifetime of about 25 years, it will even reach the year 2050, in which weather dependent renewable energy will be much more dominant than today. Therefore, simulations are performed for 2030 and 2050. For the electricity price calculation, assumptions are made for the total installed capacity of solar and wind power in the whole of The Netherlands, as well as for the geographic spread of this installed capacity over the land area and the offshore exclusive economic zone in the North Sea. This installed capacity is simplified by concentrating it in 12 locations divided over this area. The installed wave power capacity in 2030 and 2050 will most probably not have a relevant influence on the electricity price and is neglected for the Netherlands as a whole. Other necessary assumptions are the future electricity demand profile and the capacity of the flexible load that will be available at that time (interconnection, hydrogen production, electric cars, electric heaters etc.).

From literature, the cost of conventional power fuelled by natural gas and hydrogen is derived which serves as back up power for hours with low wind, solar and wave power production. Based on all these assumptions, a pricing curve is constructed reaching from sub zero at abundant renewable supply, to a maximum value at zero renewable supply. With the model, scenarios of future developments in installed wind, solar and wave power, but also in e.g. hydrogen production, electric heaters and other flexible loads, can be examined and the sensitivity of the optimization of the multi-source park design can be determined.

We start with a description of the renewable energy system that is being built by the countries around the North Sea. Following this, a first-order pricing model is described with which the hourly electricity price can be simulated. With this hourly electricity price, the revenues of the TNW multi-source park can be simulated for wind, solar and wave power separately. The influence of intraday battery storage is investigated.

II. Renewable electricity system

The countries around the North Sea are building out a renewable electricity system at a remarkable speed. In the Ostend Declaration, the energy ministers of Belgium, Denmark, Germany, France, Ireland, Luxembourg, the Netherlands, Norway and the UK have set targets to install 120 GW of offshore wind in 2030 and 300 GW in 2050 [3]. The Netherlands have set offshore wind targets of 21 GW in 2030 [4] and 70 GW in 2050 [5]. Recently the government also set a target of 3 GW offshore floating solar in 2030 [6].

At the same time international interconnection in the offshore space is being increased. Several countries, like Belgium, Germany, Denmark and the Netherlands, are also developing Energy Islands (see Fig. 1) [7]. These artificial islands will serve as hubs to which several multi-source parks can be connected and on which multiple auxiliary systems can be installed like battery storage, power-to-X converters, data centres, HVDC equipment and interconnection with other countries. Also, maintenance services and accommodation for personnel can be installed on the islands.

Fig. 1. Artist impression of the Danish energy island VindØ (image source: VindØ consortium).

Multi-source offshore renewable energy parks can play an important role in this emerging renewable energy system. By combining wind, solar and/or wave energy in one park, more efficient use can be made of the available space (see Fig. 2).

Fig. 2. Artist impression of a multi-source offshore renewable energy park consisting of wind and solar installations (source: EU-SCORES).

In the EU-SCORES project, the first multi-source offshore energy parks will be demonstrated. The company Oceans of Energy (OOE) will demonstrate a 3 MW offshore floating solar PV plant off the coast of Belgium and the company CorPower will demonstrate an array of four wave energy devices off the coast of Portugal with a total installed capacity of 1.2 MW [8]. The demonstrations will focus on the complementary production profiles of wave and solar to neighbouring wind parks, as well as the electrical integration in existing infrastructure. OOE and CorPower will be supported by 15 partner companies and institutions from nine European countries.

These developments are part of the complete overhaul of the energy system, from a fossil fuels-based system to a renewables-based system. The big difference between these two systems is that fossil fuels deliver dispatchable power that can be delivered on demand. The main renewables (solar and wind) are non-dispatchable, or only dispatchable in the sense that they can be switched off (curtailment). A system with a base load of solar and wind needs a method to balance supply and demand on an hourly basis, and the day-ahead electricity market price will serve as this intermediate to balance supply and demand.

Since the installed capacity of solar and wind will be much higher than the peak electricity demand, there will also be an important role to play for flexible loads. These are processes that only switch on when the electricity price is below a certain level. For example, the Netherlands is planning to install 70 GW of offshore wind power in 2050, while the average electricity demand will be around 25 GW at that time [9]. The surpluses will be consumed by these flexible loads.

There are also other options than solar, wave and wind for a future Dutch zero CO_2 electricity system like example biomass and nuclear power. The installed capacity of biomass electricity production is now around 1.5 GW in the Netherlands. About half of this is biogas and the other half is mostly wood pellets that are co-fired in coal plants. The government wants to stop this co-firing in 2025 since the coal plants are phased out. The Dutch government is planning to build two new nuclear power stations with a total installed capacity of 3 GW. The cost level of nuclear is now around 123 euro/MWh [10], so a fully renewable system will be a factor of 2 to 3.5 lower in cost (see VII]). Nuclear power can only compete if strong cost reductions are assumed for future nuclear plants and if the Dutch government guarantees the financing during development as well as the future electricity price [10].

DMEC created an infographic for the Dutch situation for a renewable electricity system with the technologies under development and their role in the system (see Fig. 3). Berenschot and Witteveen have performed simulations for the optimal electricity system for the Netherlands for the year 2050 [9,10]. These simulations generally show that a fully renewables-based system is not only possible but also cost effective in a zero CO_2 emission energy system. Within the EU-SCORES consortium LUT University of Finland is specialized in this work.

In the projection for the year 2050, we assume around 145 GW installed solar and wind capacity in 2050 [5,9], of which around 75 GW wind and 70 GW solar. The duration curve (thick black line in the graph) shows the hourly power production of these plants sorted from the highest (left side) to the lowest (right side) and expressed as a percentage of the maximum power.

Almost the whole year round the solar and wind production is sufficient to fulfil the peak and base load electricity of the Netherlands (dashed horizontal lines for peak and base load). If the solar and wind parks produce around 20% of their maximum capacity, they already reach this production level. So we could call this the baseload production level.

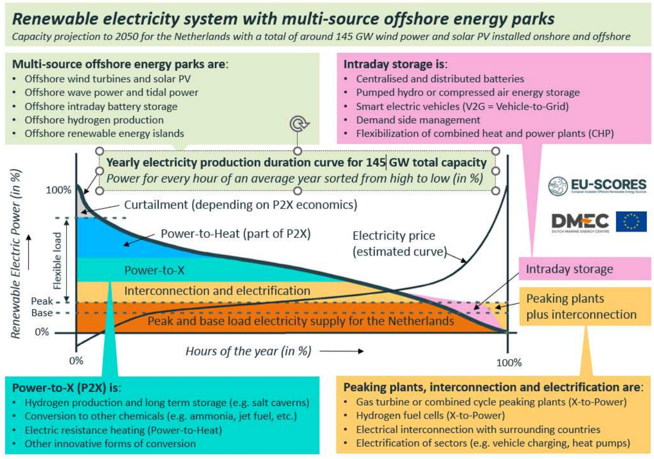

Fig. 3. Infographic for the future renewable electricity system with multi-source parks. Capacity projection for the Netherlands with a total (onshore and offshore) installed capacity of around 145 GW wind and solar.

At the right side of the graph we see that there are some periods where the baseload production is not reached. In that case the electricity price goes up (thin black line) and other, more expensive, technologies step in to cover the demand.

Because of the differences in electricity price that will occur within a single day (e.g. night and day on a clear summer day), there will be a business case for intraday electricity storage, like battery storage. Only if these intraday storages are not able to supply sufficient demand, the peaking plants will be switched on to deliver the remaining power. These are the most expensive producers in the system (in euro per MWh) and they will use green hydrogen or biogas to deliver power (see III). According to a recent simulation study [11], these peaking will be open cycle gas turbines. Combined cycle plants (gas turbines with an extra steam cycle) will be too expensive (in euro/MWh), because of the rather low full load hours of the peaking plants (in the order of magnitude of 500 hours per year).

On the left side of the graph we see that there will be large surpluses, which will be used to supply electricity to surrounding countries (interconnection) or to deliver electricity to sectors that nowadays still mostly run on fossil fuel (electrification). Remaining surpluses will be converted to hydrogen, to other chemicals or directly to heat (together called Power-to-X; where X can be anything). There might still be a small surplus for which there is no application (grey top left part), because it only occurs occasionally with strong winds and clear skies across the country. During these hours, solar and wind plants might have to reduce their production (curtailment), which is financially not a burden but a benefit as the electricity price will be negative during these hours (thin black line).

Wave and tidal energy will have their role in this emerging renewable power system. Electricity prices will be high when there is not much production of wind and solar. For the Netherlands, DMEC calculates with an installed wave capacity of 150 MW in 2030 and 1.5 GW in 2050. Wave power is produced by wind shear, however waves can roll on for thousands of kilometres. The waves that batter the Portuguese coast are also generated in the more northerly Atlantic Ocean and thus far less related to local winds than the waves in the Dutch North Sea, which are mostly generated by more local winds. The good wave potential along the European Atlantic coasts can deliver supplementary production to solar and wind production [12]. Wave energy potentials like these can be found all around the world's oceans. Tidal power has the advantage that it is not related to wind and solar power and it is fully predictable. In The Netherlands the potential is of regional importance, since it is concentrated at or near the coast (DMEC calculates with around 250 MW installed capacity in 2050).

III. ELECTRICITY PRICE MODEL

In the future renewable electricity system, based predominantly on wind and solar power, the day ahead electricity price will fluctuate with the weather. In the Netherlands this effect is now already visible, since there are hours that the production of wind and solar power is higher than demand. A linear relation between the electricity price and the demand coverage ratio of solar plus wind power is appearing (see Fig. 4). The demand coverage ratio gives the percentage of solar plus wind power in the coverage of the Dutch electricity demand [13]. The figure shows the daily electricity price as a function of the daily demand coverage ratio for the first quarter of 2023, with the data for April 2023 highlighted in red. We see a clear reduction of the electricity price at higher demand coverage ratio's. There is a linear correlation between the data points with an R^2 of 0.74.

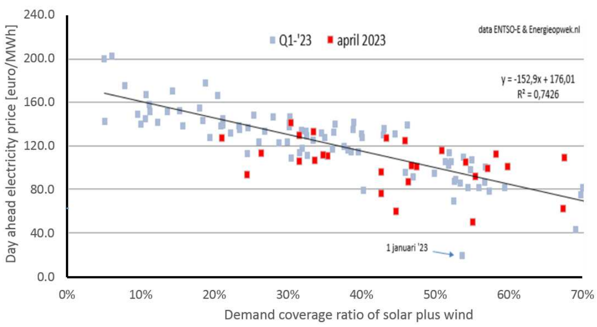

Fig. 4. The daily day ahead electricity price as a function of the demand coverage ratio of solar plus wind power in the coverage of the daily Dutch electricity demand for the first quarter of 2023 plus April 2023.

Because of the crisis in Ukraine the electricity price was exceptionally high in the first quarter of 2023. Fig. 5 shows the same linear relation for Q1 2023 with the linear relations for Q1 to Q4 of 2020 and Q1 and Q2 of 2021 [14]. In 2020, there was no effect yet from the Ukraine crisis and the electricity price in The Netherlands at zero-coverage ratio was predominantly determined by the natural gas price in which Gazprom was the main market party. The zero-coverage ratio price was about 3.5 times higher in Q1 2023 than the average zero-coverage ratio price in 2020. Where the 100% coverage ratio is sub zero in 2020, it was around 23 euro/MWh in 2023. This can be explained mainly by increased export prices to the surrounding countries where the prices were also high in Q1 2023 [15]. In the second quarter of 2021, the zero-coverage ratio price was already rising because Gazprom was reducing capacity for maintenance reasons.

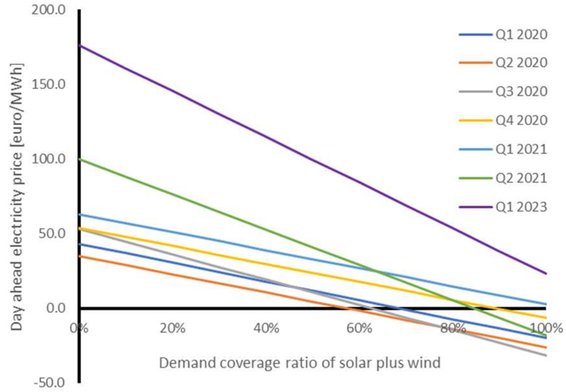

Fig. 5. The daily day ahead electricity price as a function of the demand coverage ratio of solar plus wind power in the coverage of the daily Dutch electricity demand for the first quarter of 2023, as well as for all quarters of 2020 and the first two quarters of 2021.

Based on this linear relation between the electricity price and the wind plus solar coverage ratio, we can now construct a linear price model for the future renewable electricity system. However, in the future there will not only be non-flexible demand but also flexible load (electrification). The flexible load will be switched on and off depending on the hourly electricity prices. In the current electricity system, there is hardly any flexible load and also the pricing scheme of the energy companies is not yet suited, although companies that are offering dynamic hourly prices are emerging. In 2050, the flexible load can well be bigger than the non-flexible demand [10]. Therefore, the linear relation between the electricity price, the demand and the flexible load could look like this (see Fig. 6).

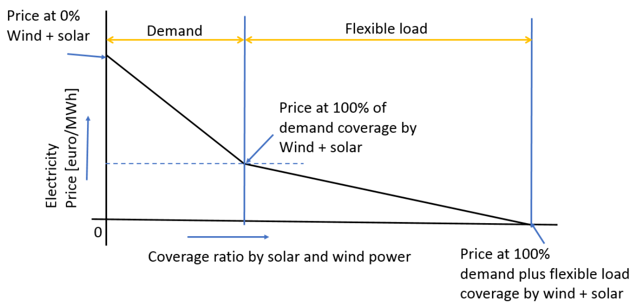

Fig. 6. Linear electricity price model consisting of two linear parts, one for the non-flexible demand and one for the flexible load.

The flexible load is switched on whenever the prices are below a certain threshold for cost effective operation. This depends on the type of flexible load like electricity export, vehicle charging, H_2 production or direct heat production. The installed capacity of flexible load will follow the developments at the supply side of the market. The more solar and wind capacity will be installed, the lower the electricity prices will get and the more flexible load capacity will be added, thereby increasing the electricity prices again. This is the normal behaviour of a supply-demand market.

For 2030 and 2050 we can now construct such price versus coverage ratio relations, however we need three assumptions for this. The first assumption is that the electricity price at zero renewable coverage ratio is x euro/MWh. The second assumption is that flexible load applications only switch on below an electricity price of y euro/MWh and the third assumption is that the installed capacity of flexible load is z % of the total installed renewable capacity. These three assumptions are determined for 2030 and 2050. With the results of the simulations, we can check if the yearly revenue for the renewable power producers is acceptable and also if the yearly electricity costs for the fixed demand and the flexible load is reasonable.

First assumption: Zero renewable coverage price

In the future renewable electricity system in 2050, the zero RE coverage ratio technology will be mainly open cycle gas turbines (OCGT) fired by green hydrogen or biogas. According to a recent study for hydrogen driven OCGTs, the LCOE of the OCGT will be especially dependent on the hydrogen costs (see Table 1) [11]. We can see that these prices are in the same range as the zero-coverage ratio electricity price in Q1 2023. These peaking plants can also deliver grid balancing services in cooperation with battery storage.

TABLE 1

LEVELIZED COST OF ELECTRICITY AS A FUNCTION OF THE INSOURCE H_2 PRICE FOR A 100% H_2 FIRED OCGT AT AROUND 800 ANNUAL OPERATING HOURS (450 MW ELECTRIC CAPACITY AND 44% EFFICIENCY)

Insource	Insource	OCGT
H_2 Price	H_2 price	LCOE
euro/kg	euro/MWh	euro/MWh
1	25	128
1.5	38	164
2	51	198

The flexible load electricity price from offshore multi-source parks will be around 20 euro per MWh in 2050 (see chapter VII). According to an IEA report from 2019 [16] the resulting H_2 production price will be around 1.5 euro per kg (at 6000 full load hours and a CAPEX of 450 euro/MWe for the electrolysers) and so the LCOE of the OCGT electricity will be around 164 euro/MWh. Since this value suggests a too high accuracy, we have set the value to 150 euro/MWh for 2030 as well as 2050. In 2030 this will be partially combined cycle gas turbine plants (CCGT) fuelled by natural gas (making relatively few hours) and in 2050 it will be OCGT hydrogen electricity production.

Second assumption: Price level below which first flexible load applications switch on

We estimate that from below an average 50 euro/MWh export to other countries becomes interesting (when the renewable coverage ratio in The Netherlands is higher than in the surrounding countries). The next flexible load could be hydrogen production below around 40 euro/MWh and below around 30 euro/MWh direct heating will become attractive. So the starting point for the flexible load applications is set to 50 euro per MWh. This value is set the same for 2030 and 2050, since competition with fossil sources (including CO_2 tax costs or CO_2 storage costs) do not allow higher prices (see Fig. 5).

Third assumption: Installed amount of flexible load capacity

In a future fully renewable electricity system, the main flexible load will be hydrogen production. In a recent system modelling study [9] the installed capacity of hydrogen production for 2050 is set at 45 GW for the Netherlands for a scenario where import dependency is reduced. The installed capacity flexible load is directly influenced by the installed capacity renewable production in this supply and demand market. So we have set the installed capacity flexible load in a direct relation to the installed renewable production capacity (35% in 2030 and 50% in 2050).

TABLE 2

ELECTRICITY PRICE AS A FUNCTION OF THE RENEWABLE ENERGY PRODUCTION FOR THE NETHERLANDS IN 2030 AND 2050

	RE Power	Price	RE Power	Price
	GW	euro/MWh	GW	euro/MWh
RE coverage ratio	2030	2030	2050	2050
0% of demand	0	150	0	150
100% of demand	17	50	24	50
100% of demand + flex load	35	0	97	0

Table 2 gives an overview of the assumptions for the electricity price versus RE coverage ratio for 2030 and 2050. At even higher RE production, negative prices can occur. Fig. 7 shows the resulting electricity price curves for these years. We especially see the large increase in expected flexible load between 2030 and 2050. All three assumptions will need more detailed support from literature sources in the near future.

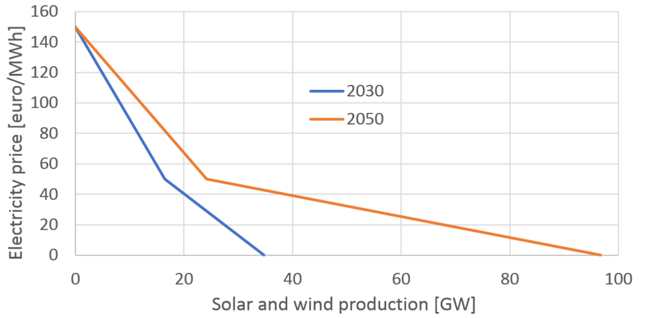

Fig. 7. Electricity price as a function of the renewable energy production for the Netherlands in 2030 and 2050.

IV. Geographic Spread

The onshore and offshore area of the Netherlands is relatively small compared to other European countries like France and the UK, but still there is an effect of the geographic location on the solar, wind and wave production. This geographic distribution of the renewable generation has a direct influence on the electricity price. The Netherlands has a single day ahead electricity market, so all the renewable production is aggregated to a total renewable production over the land and sea area. To be able to calculate this total production we have made a simplified geographic spread over the land and sea area, consisting of twelve locations of which seven onshore and five offshore (see Fig. 8). The locations are chosen at KNMI (Dutch meteorological institute) weather stations, so that we have the most optimal weather data available. All the renewable production capacity is concentrated in these 12 locations.

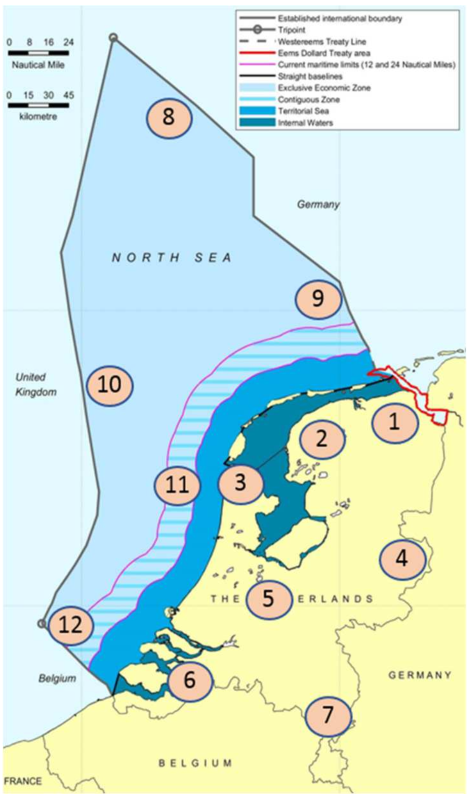

Fig. 8. Simplified geographic distribution consisting of twelve locations in which the renewable production is concentrated.

Table 3 shows the twelve locations

TABLE 3
THE GEOGRAPHIC LOCATION IN WHICH THE RENEWABLE PRODUCTION CAPACITY IS CONCENTRATED (LOCATIONS IN DEGREES)

	Location	**KNMI station**	**North**	**East**
1	Groningen	Eelde	53.120	6.580
2	Friesland	Leeuwarden	53.220	5.520
3	Noord Holland	De Kooy	52.930	4.780
4	Overijssel	Twenthe	52.270	6.880
5	Utrecht	De Bilt	52.100	5.180
6	Brabant, Zeeland	Woensdrecht	51.540	4.350
7	Limburg	Ell	51.200	5.770
8	Northern part of territorial waters	A12-CPP	55.399	3.810
9	Ten Noorden Waddeneilanden	Gemini BG OHVS2	54.037	6.042
10	Nederwiek, Lagelander, IJmuiden ver	K13-A	53.218	3.219
11	Hollandse Kust	Hoorn A	52.918	4.150
12	Borssele wind park	Euro platform	51.998	3.275

Table 4 shows the distribution of the renewable production capacity over these twelve stations for 2030. The total (in GW) is the total installed wind or solar capacity onshore or offshore in the whole of the Netherlands.

TABLE 4
DISTRIBUTION OF THE INSTALLED OFFSHORE AND ONSHORE SOLAR AND WIND CAPACITY OVER THE 12 LOCATIONS FOR 2030

2030	**Wind**	**Wind**	**Solar**	**Solar**
	Onshore	**Offshore**	**Onshore**	**Offshore**
TOTAL GW	**6.7**	**21.0**	**21.4**	**3.0**
Location				
1	18.0%		14%	
2	10.9%		6%	
3	12.6%		10%	
4	2.5%		14%	
5	28.4%		17%	
6	25.5%		21%	
7	2.1%		18%	
8		0%		0%
9		20%		0%
10		53%		0%
11		20%		100%
12		7%		0%
Total	*100.0%*	*100.0%*	*100.0%*	*100.0%*

The percentages give the distribution of this installed capacity over the land or sea area. Until 2030, these are the planned capacities and locations of the Dutch government. For 2050 an estimation is made where the extra capacity would be installed. Table 5 shows the distribution over the twelve locations for the year 2050.

TABLE 5
DISTRIBUTION OF THE INSTALLED OFFSHORE AND ONSHORE SOLAR AND WIND CAPACITY OVER THE 12 LOCATIONS FOR 2050

2050	**Wind**	**Wind**	**Solar**	**Solar**
	Onshore	**Offshore**	**Onshore**	**Offshore**
TOTAL GW	**5.0**	**70.0**	**50.0**	**20.0**
Location				
1	18.0%		14%	
2	10.9%		6%	
3	12.6%		10%	
4	2.5%		14%	
5	28.4%		17%	
6	25.5%		21%	
7	2.1%		18%	
8		50%		0%
9		10%		5%
10		26%		50%
11		10%		40%
12		4%		5%
Total	*100.0%*	*100.0%*	*100.0%*	*100.0%*

The installed onshore wind capacity in 2050 is an estimation by DMEC based on the relatively few full load hours of onshore wind and the steeper learning curve of offshore wind. Most scenario's expect around 10 GW of onshore wind [9,10].

V. INTRADAY STORAGE

Intraday storage will play a significant role in the renewable electricity system of the future. The Dutch transmission and distribution system operators have received already 34 GW of battery storage applications [17]. While much of these are only in a planning phase, it shows that there is a lot of activity in this field. For offshore multi-source parks there is also the option to install batteries on the wind turbines or on dedicated substations for the multi-source parks as a whole (see Fig. 9 and 10). With battery storage at the source, curtailment can be reduced and the capacity factor of the substation and export cable can be raised. Moreover, the electricity delivery can be shifted to hours with higher prices.

For TNW we have calculated with a battery storage with a capacity of 1120 MWh. This implies 1.6 hours the cable capacity of 700 MW. Such a capacity of 1120 MWh can be realized with the dedicated substation in Fig. 10.

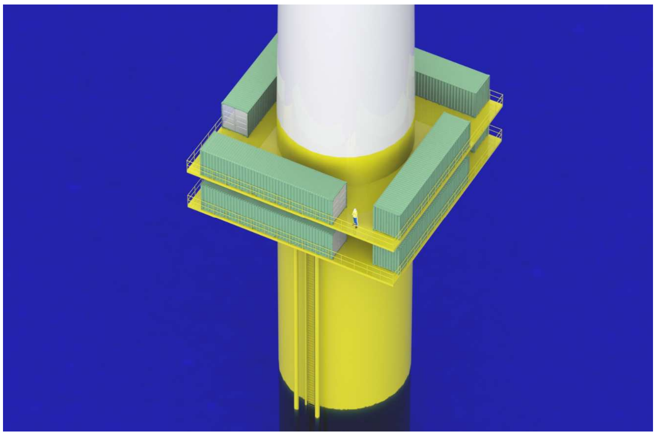

Fig. 9. Battery storage mounted to a wind turbine. Eight containers with 40 MWh total storage capacity (DMEC visualization).

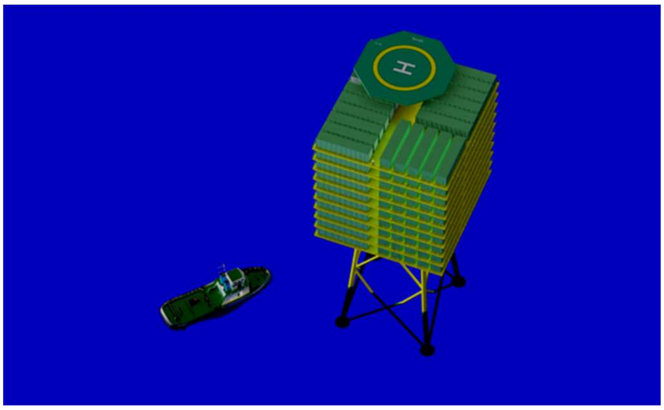

Fig. 10. Battery storage on a dedicated substation for the multi-source park as a whole, consisting of 220 containers with a total capacity of 1120 MWh (DMEC visualization).

VI. THE MULTI-SOURCE SIMULATION MODEL

A. *Demand model*

For the Dutch (non flexible) electricity demand in 2030 and 2050 we used hourly demand data over the year 2017 multiplied by a factor for the anticipated rise in the demand because of electrification. In 2017 the average demand was 13 GW, in 2030 an average demand of 16.5 GW is anticipated and in 2050 of 24.2 GW [18].

With this approach, a realistic daily and weekly pattern is generated with a seasonal effect. However the daily pattern is not influenced by the daily weather circumstances like cloudiness (e.g. influencing lighting) and ambient temperature (e.g. influencing heating).

B. *Wave model*

For the wave model calculations the power matrix that was published by WaveStar is applied [19]. The power matrix is based on prototype performance measurements as well as an estimation of future improvements (see Table 6).

The two input variables for TNW are obtained from the ResourceCode marine data toolbox. The ResourceCode database provides peer-reviewed sea-state hindcast data and includes the highest resolution wave model for North-West Europe [20].

TABLE 6
WAVESTAR PROTOTYPE ELECTRICAL POWER MATRIX IN KW AS A FUNCTION OF SIGNIFICANT WAVE HEIGHT (H) AND PEAK WAVE PERIOD (T)

Wave height H (m)	Wave period T (sec)										
	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
0.0-0.5	0	0	0	0	0	0	0	0	0	0	0
0.5-1.0	0	49	73	85	86	83	78	72	67	63	59
1.0-1.5	54	136	193	205	196	182	167	153	142	132	123
1.5-2.0	106	265	347	347	322	294	265	244	224	207	193
2.0-2.5	175	429	522	499	457	412	372	337	312	288	267
2.5-3.0	262	600	600	600	600	540	484	442	399	367	340
3.0-	Storm protection										

C. *Solar PV model*

The power generation by PV panels is quantified with the following formula:

PPV = A Eff H PR

Where, PPV [W] is the generated power by the PV panels, A [m^2] is the PV capture area, Eff [-] is the PV efficiency, H [W/m^2] the incoming solar irradiance, and PR [-] the performance ratio; a coefficient that accounts for losses, such as degradation, fouling and park losses. For this study, an efficiency of 20% and a PR of 0.77 is applied [21]. Satellite data from the PVGIS-SARAH2 satellite is used for the hourly irradiance, processed by PVGIS [22]. PVGIS does not provide offshore irradiance data and we do not have irradiance data from other sources yet, for the offshore locations. So we applied the irradiance data for Den Haag for the two southern locations (numbers 11 and 12) and from Den Helder for the three northern locations (numbers 8, 9 and 10), as well as for the TNW park. The global irradiance on a plane with a slope of 40 degrees south and an azimuth of 0 degrees is applied.

D. *Wind power model*

The power generation by wind turbines in a wind farm is calculated with the formula:

Pt = 0.5 ϱ A v^3 Cp EFFpark

In which, Pt [kW] is the power generated by the wind turbine, A [m^2] is the rotor area, ϱ [kg/m^3] is the density of the air, v [m/s] is the wind speed at hub height, and Cp [-] is the power coefficient. The factor EFFpark [-] represent the wake effect of the wind park as well as the losses in the drivetrain and grid connection.

Offshore 15 MW turbine:

For the offshore wind turbines we have chosen the 15 MW NREL wind turbine design for research purposes [23]. The power curve can be described by the following parameters:

Cut in wind speed	=	3 m/s
Cut out	=	25 m/s
Rated windspeed	=	10.6 m/s
Rotor diameter	=	240 m
Cp	=	0.45
Hub height	=	140 m
EFFpark	=	90%

Onshore 5 MW turbine:

For the onshore parks an average 5 MW wind turbine is chosen with the following power curve:

Cut in wind speed	=	2 m/s
Cut out	=	25 m/s
Rated windspeed	=	12 m/s
Rotor diameter	=	130 m
Cp	=	0.35
Hub height	=	90 m
EFFpark	=	90%

KNMI [24] wind data from a height of 10 m were recalculated to the relevant hub height with a logarithmic wind shear profile with an offshore roughness length of 0.0002 m and an onshore roughness length of 0.1 m [25].

VII. RESULTS FOR THE NETHERLANDS

The simulation program calculates the electricity price for every hour of the year for the pricing zone of the Netherlands (see Fig. 11) using weather data from 2017. The volatility in the electricity price is visible.

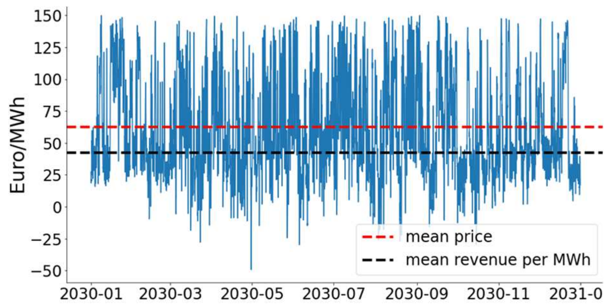

Fig. 11. Electricity price for every hour of the year 2030 (with weather data from 2017).

The electricity prices can be arranged from low to high in the shape of a duration curve. Fig. 12 gives the price duration curve for 2030 and 2050.

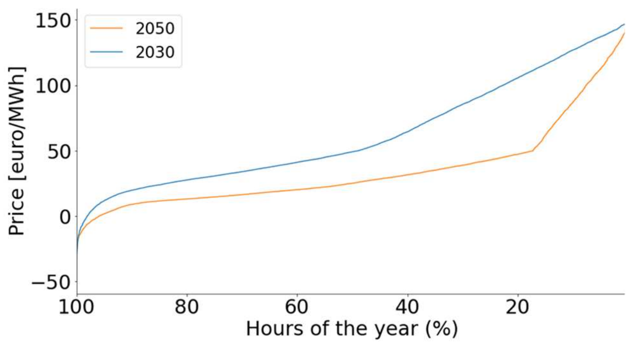

Fig. 12. Price duration curve for the year 2030 and 2050 (weather data from 2017).

The electricity prices are directly related to the renewable electricity production. See Fig. 13 for the renewable production duration curve.

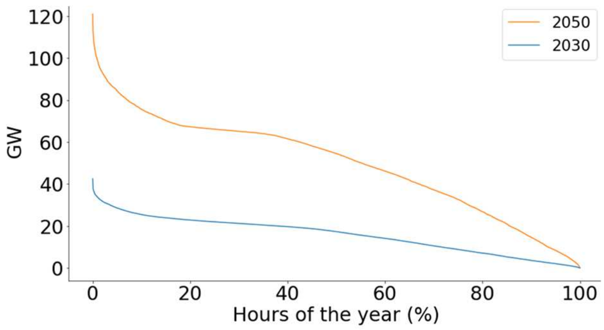

Fig. 13. Renewable production duration curve for 2030 and 2050 (weather data from 2017).

With increasing installed renewable capacity, production will rise and the electricity prices will be reduced. Table 7 gives an overview of the simulated electricity revenues for the renewable energy production types for 2030 and 2050.

TABLE 7
REVENUE FOR THE THREE TYPES OF RENEWABLE ELECTRICITY PRODUCTION FOR 2030 AND 2050 (WEATHER DATA FROM 2017)

	Revenue	Revenue	
RE type	**2030**	**2050**	
Wind	42.2	21.7	Euro/MWh
Solar	41.8	19.3	Euro/MWh
Wave	51.9	24.1	Euro/MWh
All types	42.1	21.4	Euro/MWh

We can see that wave power receives a better price for its production than solar and wind in the Dutch bidding zone (23% higher price than wind in 2030 and 11% higher in 2050). Especially the prices in 2050 seem rather low, although such a price level could be necessary if the Netherlands (or the EU as a whole) aims to produce hydrogen also locally, in stead of depending fully on hydrogen imports. Learning curve studies can give more certainty on this.

The average price over the year is calculated at 62.5 euro/MWh in 2030 and 35.0 euro/MWh in 2050. This will also be about the price that tidal current power will receive, since tidal power is evenly distributed over the year. The 2030 average price is relatively high, because we assumed that green hydrogen OCGT plants are used for the zero-coverage ratio electricity supply, while most probably this will still be partially natural gas driven CCGT plants.

The revenue of the H_2 OCGT peaking plants is calculated at 114.2 euro/MWh in 2030 and 110.0 euro/MWh in 2050. The capacity factor of the peaking plants is calculated at 15.6% for 2030 and 5.1% for 2050. These capacity factors are based on the maximum non-flexible demand in the respective years (24.1 GW in 2030 and 35.3 GW in 2050). A capacity factor of 5.1% is equal to 447 full load hours per year. So the mean revenues for peaking plants will be lower than the 150 euro/MWh at zero RE coverage ratio, but can be complemented with extra revenue from grid services like from the intraday market, from the balancing market or possibly from a reserve capacity market. The H_2 OCGT plants bring security of supply to the system and this could be valued in its own right.

VIII. RESULTS FOR TNW MULTI-SOURCE PARK

Now that we have characterized the electricity prices in the Dutch bidding zone in 2030 and 2050, we can introduce the new TNW wind park in this system. For the multi-source park we add 778 MW solar power plus 56.4 MW wave power to the 779 MW wind power. The cable capacity remains at 700 MW. The 56.4 MW wave power is a DMEC calculation of the wave power capacity that can be installed at the northern edge of the wind park. The cable capacity is kept constant, because the aim is especially to raise the utilisation of the electrical connection.

Based on the cable connection capacity, the capacity factor is increased from 62.5% to 79.9% by adding the solar and wave capacity. Fig. 14 shows that also the number of hours that the multi-source park production is below 20% cable capacity (baseload), is reduced. Especially the periods longer than 20 hours are reduced.

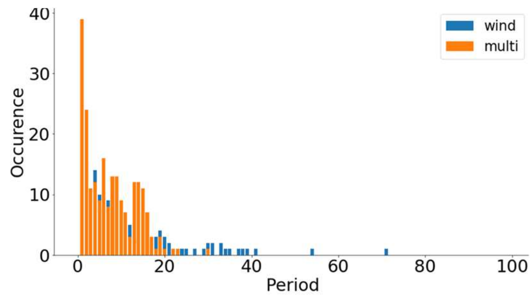

Fig. 14. Number of occurrences of periods (in hours) with a renewable production below 20% of cable capacity. The periods are expressed in hours (weather data from 2017).

The revenues for the different renewable energy production types for TNW are shown in Table 8.

TABLE 8
REVENUE OF THE THREE TYPES OF RENEWABLE PRODUCTION IN THE TNW PARK (WEATHER DATA FROM 2017)

	Revenue	Revenue	
RE type	**2030**	**2050**	
Wind	46.5	22.6	Euro/MWh
Solar	42.3	18.9	Euro/MWh
Wave	51.9	26.7	Euro/MWh
All types	46.0	21.7	Euro/MWh

There are differences between the TNW revenues per type and the revenues per type for the Netherlands as a whole. The TNW location has a relatively good wind and wave resource, leading to somewhat higher revenues per kWh. The solar result is influenced by the use of coastal data. The curtailment of production is rather high, with 9.2% of generated yearly production, but this generally occurs at very low price levels. This can be reduced with intraday storage.

IX. Flexible loads

In the future renewable electricity system, interconnection and flexible loads will play an important role, as discussed. The simulation program calculates the following operating hours and average price levels for the different price levels below which interconnection and flexible loads can start to operate (see Table 9).

TABLE 9
AVERAGE YEARLY PRICE LEVELS AND AMOUNT OF HOURS FOR DIFFERENT PRICE LEVELS BELOW WHICH INTERCONNECTION AND FLEXIBLE LOADS CAN START TO OPERATE (WEATHER DATA FROM 2017)

Price	Hours	Price	Hours	Price
Level		**Euro/MWh**		**Euro/MWh**
euro/MWh	**2030**	**2030**	**2050**	**2050**
< 50	4478	29.5	7251	22.5
< 40	3384	24.5	6259	19.0
< 30	2098	18.2	5060	15.2

X. Battery storage

An offshore battery with 1120 MWh capacity has been added to the TNW park to make a first-order approximation of the increase in baseload supply. This 1120 MWh can store the full capacity for 1.6 hours. The battery is controlled in such a way that it will minimize the number of hours in which the park output is below the baseload (below 20% of cable capacity). The battery charges when the park output is larger than 1.5 times the baseload and when curtailment occurs. It discharges when the park output is below the baseload. Charging and discharging occurs with 90% efficiency. Such a relatively small battery can reduce the hours that the production of the multi-source park is below 20% of cable capacity, from 1065 to 876 hours (a reduction of 18%).

Future efforts will focus on integrating a more advanced battery control strategy. Based on a calculation of the day-ahead price forecast, a financial optimisation will be made determining the hours that the battery will charge or discharge (energy arbitrage).

XI. Discussion

The presented results have a preliminary nature, because we do not have the offshore solar data available at this point in time. As explained we are using coastal solar data instead. The EU-SCORES project will run for more than a year from now, so we have time to refine the simulations.

Although the results are preliminary, they provide a novel first-order approximation of a financial assessment of multi-source parks in the form of hourly electricity prices. In future work we will consider different price scenario's and improve the battery storage simulations.

In the coming year the partners in the EU-SCORES project will cooperate with DMEC in the optimisation of multi-source park designs.

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