Open Access

Journal of Energy and Power Technology

LIDSEN Publishing Inc.

Research Article

The Physical Potential for Dutch Offshore Wind Energy

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Academic Editor: Andrés Elías Feijóo Lorenzo

Collection: Wind Energy

Journal of Energy and Power Technology
2022, volume 4, issue 4
doi:10.21926/jept.2204032

Received: August 04, 2022
Accepted: September 22, 2022
Published: October 10, 2022

Abstract

In the Netherlands, an important way to contribute toward achieving climate goals is the large-scale deployment of wind turbines in the North Sea. The North Sea is a unique location for offshore wind power thanks to its strong winds, shallow waters, and proximity to large energy users. Wind turbines generate electricity by extracting kinetic energy from the atmosphere. This kinetic energy is replenished at a finite rate through the mixing of atmospheric layers. The replenishment rate sets a physical limit to the amount of energy that can be sustainably extracted from a given area. In this study, we show that the Dutch Exclusive Economic Zone in the North Sea can sustainably host an installed capacity of approximately 59 GW on readily available space. By selecting areas fit for co-use, such as nature reserves and military zones, this amount can be increased to approximately 99 GW. With a calculated capacity factor of 45%, these areas can yield 240 and 381 TWh/yr, respectively, in the conservative and optimistic scenarios considered in this study, which correspond to approximately 39 and 62% of projected Dutch final energy demand in 2050. North Sea wind power is capable of supplying a significant amount of clean energy to Europe at large. Applying our approach to all North Sea countries combined implies that a capacity of approximately

418 GW can be sustainably installed in the North Sea under relatively conservative assumptions for water depth and distance from the shore. At a capacity factor of 43%, this can yield a power production level of as much as 1584 TWh/yr, which could satisfy approximately 40% of projected European electricity demand in 2050.

Keywords
Offshore wind energy; Netherlands North Sea; sustainability; potential; replenishment

1. Introduction

In the 2015 Paris Agreement, 195 countries agreed to keep the increase in global average atmospheric temperature to well below 2°C compared to preindustrial times and to aim for a maximum increase of 1.5°C [1]. To conform to these goals, total CO_2 emissions must be reduced to net zero by 2050 [2]. Achieving this goal requires a fundamental change in electricity generation and consumption [3].

In 2020, 70% of electricity in the Netherlands was generated by burning coal and natural gas. Nuclear energy and biomass accounted for 4% and 6%, respectively, whereas the remaining 20% was generated by solar and wind power installations [4, 5]. Keeping up with the increasing electricity demand while reaching carbon-neutral electricity production in 2050 requires large investments in both solar and wind power generation. Currently, approximately 2.5 GW of wind power is installed in the Dutch Exclusive Economic Zone (EEZ) of the North Sea [6]. The Dutch government aims to install a total of 11 GW of offshore wind power before 2030, enough to supply 40% of the current electricity consumption in the Netherlands, or 8.5% of the current energy consumption, as described in the Offshore Wind Energy Roadmap 2030 [7]. In October 2021, an initiative was announced to identify areas for an additional 10 GW before 2031, bringing the total to 21 GW [8, 9], and in March 2022, the final areas were designated by the Dutch government [10]. Projections for the total installed wind energy capacity for 2050 range from 60–72 GW [7, 11, 12].

Since offshore wind power is expected to become a major source of energy, it is important to address its longevity. Thus, in this study, the sustainability of electricity generation from wind power has been investigated. Energy production methods such as using solar panels and wind turbines are distinct from fossil-fuel-based sources because they do not release CO_2 into the atmosphere during operation. However, that does not necessarily mean that these methods are sustainable. Sustainability means that the energy source does not deplete. It is, therefore, important to determine the long-term potential of the energy sources. For solar energy, the potential is virtually limitless and cannot be depleted at the time scale considered for mankind. However, the energy potential is limited for wind power. Wind turbines generate electricity by extracting kinetic energy from the lower atmosphere. This kinetic energy is replenished via turbulent mixing with the unaffected atmospheric layers at higher altitudes. However, this process occurs at a finite rate [13, 14]. If more kinetic energy is extracted than is replenished, electricity is being generated in an unsustainable manner.

Currently, approximately 20 GW of wind power capacity has been installed on the totality of the North Sea [15]. The majority of this capacity consists of wind farms smaller than 1 GW. These wind farms typically have a power density of approximately 7 MW/km^2. The kinetic energy generation rate of the atmosphere has been calculated to be approximately 2 MW/km^2 [16], which matches empirical observations in the literature [17-20]. Thus, most existing wind farms generate electricity in a locally unsustainable manner. Currently, these farms have been placed far enough apart to allow sufficient replenishment in the open space between them. However, we are rapidly moving into a new phase of wind energy generation, in which not only the Netherlands but also Belgium, Denmark, Germany, Norway, and the United Kingdom are planning to significantly increase their wind turbine deployment [21]. WindEurope expects that up to 212 GW can be installed in the North Sea by 2050 [22]. This could create a situation in which locally unsustainable use of wind energy cannot be compensated anymore by replenishment from non-used space between future wind farms.

In this study, firstly, the space available for wind farms in the Dutch EEZ in 2050 has been determined by showing the projections for shipping lanes, nature reserves, oil and natural gas platforms, and military zones. A way to increase the available space by selecting certain areas for co-use has also been presented. Further, the physical potential for sustainable wind energy has been determined by building on and adapting the kinetic energy budget of the atmosphere (KEBA) model developed by two wind energy analysts [23]. Our calculations have been adjusted for the Dutch EEZ with wind turbine specifications that are projected to be widely used by 2050. These results have been extrapolated to other North Sea countries to estimate the physical wind power potential for Europe.

2. Materials and Methods

The North Sea is one of the busiest waters in the world. With six countries bordering the water body, large shipping routes, a diverse marine ecosystem, and abundant energy potential, the available space is limited. The Dutch section of the North Sea, or the EEZ, is an area of about 59000 km^2. Figure 1 gives an overview of the main uses of the Dutch EEZ in 2022 [24]. Fishing has been left out in this figure since it is allowed everywhere except in and around wind farms and certain nature reserves. Surface mineral extraction, in the form of sand and gravel production, has also been left out in Figure 1, since it occupies little space and is mainly performed in otherwise unused areas. Table 1 lists the percentages of the areas in the Dutch EEZ reserved for specific uses. Today, these uses already share space in many locations and might increasingly do so in the future. Thus, the percentages do not add up to 100% and thus are not directly indicative of determining the space still available.

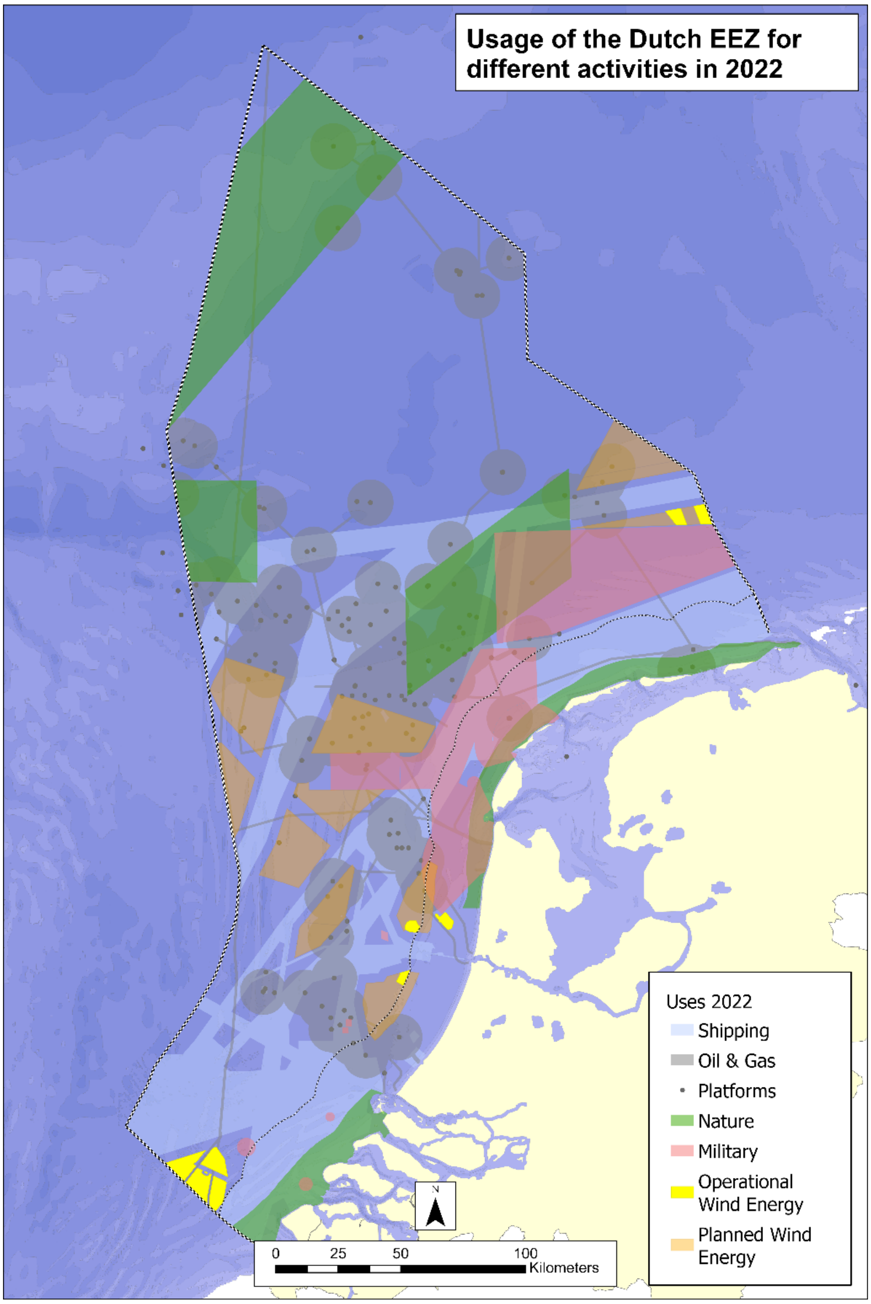

Figure 1 The Dutch EEZ and its uses for different activities in 2022 [24].

Table 1 Usage of the Dutch EEZ for different activities in 2022.

USE	AREA (KM^2)	SHARE OF DUTCH EEZ
SHIPPING	17472	30%
OIL & GAS	15869	27%
NATURE	11220	19%
MILITARY	6468	11%
OPERATIONAL WIND ENERGY	406	0.7%
UNUSED	20757	35%

N.B. Percentages do not add up to 100% as a consequence of co-use.

The space reserved for these uses is expected to see drastic changes over the next 30 years. To determine the upper bounds of the available space for wind energy in 2050, the official projections provided by the Dutch government for shipping lanes, oil and natural gas infrastructure, nature reserves, and military zones [6] were used in this study. For each use, a conservative and an optimistic scenario was developed.

After identifying the available space for wind power generation in 2050, the energy yields were estimated by building on the KEBA model developed by Kleidon and Miller [23]. This simple physics-based model determines the energy budget of a region by using the horizontal and vertical kinetic energy influx of a given volume encompassing a wind farm. The influx has to be equal to the sum of the horizontal downwind outflux, dissipative losses due to friction and wakes, and energy removal by wind turbines:

$$\Phi_{in,h} + \Phi_{in,v} = \Phi_{out,h} + D_{fric+wake} + P_{el} \tag{1}$$

where Φ_{in} and Φ_{out} denote the inward and outward energy fluxes, respectively, $D_{fric+wake}$ represents the dissipative energy losses due to friction and wakes, and P_{el} represents the electrical power generation of the turbines. As inputs, the model requires a wind speed distribution, a given rectangular area, a set of wind turbine specifications, and the total number of installed turbines. Using this approach, it is possible to determine the trend of reduction in the energy yield as a function of increasing power density. Kleidon and Miller have shown that the estimates generated with their stylized model compare well to the simulation results obtained using the high-resolution weather research and forecasting (WRF) model [23, 25]. The high-resolution atmospheric WRF model is often used for calculating the wind energy potential [26].

To determine the wind energy potential for the Dutch EEZ, the input parameters for the KEBA model were required to be adjusted. First, a wind speed profile that is specific to the North Sea [27] was chosen. The rectangular area was chosen based on the identified available space. Then, the wind turbine specifications were adjusted such that they reflected the wind turbine types that are projected to be widely deployed in 2050. Therefore, the specifications of the new General Electric Haliade-X turbine, with a rotor diameter of 220 m and a rated capacity of 14 MW [28], were used. The construction of the first operational prototype Haliade-X turbine was recently completed at the Maasvlakte in Rotterdam.

The KEBA model updated with these wind turbine specifications, the Dutch offshore wind speed profile, and the available space in the North Sea according to the official governmental documents was employed, and calculations were done in the conservative as well as optimistic scenarios with five different power densities (1, 2, 4, 6, and 8 MW/km^2, respectively). Thereby, the capacity factor and power yield for all 2×5 configurations were calculated. Subsequently, the atmospheric replenishment rate of kinetic energy was investigated, and an optimal power density that would ensure long-term sustainable electricity generation was determined.

3. Results

Shipping – Shipping routes, clearways, and approach areas to seaports take up a combined space of 30% of the Dutch EEZ. Shipping is vital for the Netherlands as a large part of the economy is dependent on imports and export. In August 2013, all major shipping routes were re-evaluated and modified, resulting in the zones shown in Figure 1 [29]. These zones are not expected to change in the foreseeable future. Although a large area is reserved for shipping, the co-use of shipping space is possible with other functions, such as nature reserves, military zones, and oil and natural gas platforms, along with their associated safety zones. Most nature reserves focus on preserving flora and fauna in and on the seabed, which shipping does not usually disturb. Military exercises can be planned such that no large ships pass during exercises, and oil and natural gas platform safety zones only prohibit permanent structures from being built. However, in the case of wind farms, ships larger than 24 m in length are restricted from passing within a range of 500 m from them. Smaller ships can pass through but not for fishing, and they are not allowed to drop anchors [29].

One could argue that there is a trend toward increasingly bigger turbines. Larger wind turbines can and normally should be placed further apart. It is, thus, not unthinkable that in the future, constructing wind farms around certain shipping lanes can become a possibility. However, in the present study, we have abstracted from this possibility because the area gained from such co-usage is probably small. Thus, we assumed that in the conservative and optimistic scenarios, no additional space is made available for wind energy, as pointed out in Table 2.

Table 2 Space in the Dutch EEZ reserved for shipping.

Shipping	Reserved space in 2022	Expected space in 2050	
		Conservative	Optimistic
Area (km^2)	17472	17472	17472
Share of Dutch EEZ	30%	30%	30%

Oil and gas – The North Sea contains large oil and natural gas reserves. In the Dutch EEZ, 155 production installations are currently operational, including drilling platforms, subsea stations, side-taps, and satellite platforms. These installations, the pipelines between them, and the connections to the shore have a safety zone of 500 m. In these safety zones, the building of permanent structures is prohibited [6]. If the installation is outfitted with a helicopter deck, the safety zone increases to 9.26 km (5 NM). This additional precaution is taken to ensure safe flying routes for helicopters, which significantly decreases the space available for wind farms, as shown in Figure 1. The thin grey lines are the safety zones of pipelines. The bigger grey circles represent the safety zones for helicopter decks at the oil and natural gas platforms. Progress is being made to determine the approach and departure sectors for helicopters instead of designating the entire circle as a safety zone [30].

While oil and natural gas production has been an important contributor to the Dutch economy in the past, rapid decommissioning of oil and natural gas platforms is necessary to achieve national and international climate goals. In addition, multiple natural gas fields have already depleted or are nearing depletion. The Dutch Mining Law states that a nonproducing facility must be decommissioned within 10 years. Thus, in the conservative scenario, we assumed that 75% of the current space associated with oil and natural gas production would be made available for wind turbine deployment. Most platforms will be decommissioned as a result of gas field depletion. A small number of platforms might be kept operational to serve as electrolysis or carbon storage units. In addition, the radius of safety zones might be decreased thanks to developments in radar systems and helicopter technology. In the optimistic scenario, we assumed that all space associated with oil and natural gas production would be made available for wind energy. The main reason for this assumption was that it is not unimaginable that locations for wind farms will be prioritized over locations for platforms, even if they are used for electrolysis or carbon storage. Table 3 shows the reserved space for oil and natural gas platforms in both scenarios.

Table 3 Reserved space in the Dutch EEZ for oil and natural gas platforms.

Oil and natural gas	Reserved space in 2022	Expected space in 2050	
		Conservative	**Optimistic**
Area (km²)	15869	3967	0
Share of Dutch EEZ	27%	7%	0%

Nature – About 19% of the Dutch EEZ is used for nature preservation. In addition to the areas shown in Figure 1, five more areas, representing another 12%, are proposed to become Natura2000 zones [31, 32]. When all the proposed zones are accepted and implemented, roughly 31% of the Dutch EEZ will be restricted from wind farms because Dutch law forbids wind turbines from being constructed in nature reserves [6]. However, by developing new technologies, such as gentle pile driving [33] or floating wind farms, this area can be opened up for wind turbine deployment, thus, greatly increasing the total offshore wind energy potential [34]. In addition, research is being undertaken on the potential benefits of wind farms for aquaculture, oyster beds, and seaweed nurseries [35-37]. If the results of this research are positive, then it might even be advantageous to create co-use areas in the future [38].

The future possibility of co-use between wind farms and nature reserves also depends on the type of flora or fauna being preserved. Table 4 shows the current and proposed Natura2000 zones in the Dutch EEZ. These zones fall under either the Habitat Directive or the Birds Directive [6, 31]. The Habitat Directive includes the preservation of life in and on the seabed, such as seals and porpoises. The Birds Directive is designated to preserve life above water, specifically birds.

Table 4 Active and proposed Natura 2000 sites in the Dutch EEZ in 2022.

Name	*Status*	Directive type	Possible co-use	Area (km²)
Doggersbank	Active	Habitat	Yes	4650
Klaverbank	Active	Habitat	Yes	1240
Noordzeekustzone	Active	Habitat & Birds	No	1439
Vlakte van de Raan	Active	Habitat	Yes	175
Voordelta	Active	Habitat & Birds	No	835
Friese Front	Active	Birds	No	2881
Centrale Oestergronden	Proposed	Habitat	Yes	3453
Gasfonteinen	Proposed	Habitat	Yes	593
Bruinebank	Proposed	Birds	No	1292
Borkumse Stenen	Proposed	Habitat	Yes	656
Kustzee	Proposed	Habitat & Birds	No	990

In the conservative scenario, we assumed that wind turbine deployment in nature reserves would continue to be completely prohibited. In the optimistic scenario, we assumed that co-use could be realized for the nature reserves listed in Table 4 that fall under the Habitat Directive. For these areas, we assumed a lower power density to allow sufficient space between turbines for wildlife preservation. In effect, we considered 50% of the nature reserve areas to be opened up for wind turbine deployment. In addition, some nature reserves are within the 12-mile border (22,2 km) from the Dutch coast, in which no wind farms are expected to be built. Lastly, the overlapping area of nature reserves with shipping lanes was subtracted from the available space. Table 5 shows the reserved space for nature reserves in both scenarios.

Table 5 Reserved space in the Dutch EEZ for nature reserves.

Nature	Reserved space in 2022	Expected space in 2050	
		Conservative	**Optimistic**
Area (km^2)	11220	18 190	12 289
Share of Dutch EEZ	19%	31%	23%

Military – Just over 11% of the Dutch EEZ is reserved for military purposes, where shooting, flying, rescue, and mine removal exercises are performed. Co-use of military zones already exists with oil and natural gas production, nature reserves, and shipping routes [6]. However, co-use with wind farms is more difficult since wind turbines are spread out over a large area and can reach well over 250 m in height. Therefore, they cannot be placed in flying- or rescue exercise zones. Constructing turbines in zones for mine removal or shooting exercises is also impossible. The zones associated with military exercises are not expected to change soon [34, 39]. Nevertheless, the large flying zone to the North of the Waddeneilanden lies in relatively shallow waters, making it a prime location for wind farms. To achieve the Dutch climate goals, a reallocation of military activities could become subject to serious consideration. Moving zones further out to sea increases the time and fuel costs for military exercises but decreases the wind farm costs significantly since it implies shorter cables and more shallow monopiles [40]. In the conservative scenario, we assumed that no changes will be made to the current military zones. In the optimistic scenario, we assumed that the low-flying zone east of Texel will be removed and the size of the low-flying zone north of the Waddeneilanden will be decreased by 25%. Since these areas do not overlap with shipping lanes or nature reserves, they can be opened up for wind turbine deployment. Table 6 shows the reserved space for military zones in both scenarios.

Table 6 Reserved space in the Dutch EEZ for military zones.

Military	Reserved space in 2022	Expected space in 2050	
		Conservative	**Optimistic**
Area (km^2)	6468	6468	5325
Share of Dutch EEZ	11%	11%	9%

Projections for 2050 – Combining the projections of the uses above, the total space available for wind farms in 2050 in the two scenarios was identified. Here, we took into account the expected space of all uses and their overlapping regions. The sea in the Dutch EEZ is neither very deep (maximum 50 m) nor very far from shore (maximum 270 km). Wind turbine foundations up to a depth of 50 m have been shown to be possible [41], and the distance from the shore is mainly an economic feasibility concern rather than a technical one. Therefore, we assumed that no space has to be excluded based on the depth or the distance from shore. These assumptions gave a total area of 14806 km^2 or 25% of the Dutch EEZ in the conservative scenario. If we further assumed that oil and natural gas production was stopped, co-use could be realized with specific nature reserves, and some reductions could be made to the size of the military zones. Thus, an additional 10010 km^2 or 17% of the Dutch EEZ would be available, which we call the optimistic scenario. The area for both scenarios is shown in Table 7 and Figure 2.

Table 7 Reserved space in the Dutch EEZ for wind farms.

Wind	Reserved space in 2022	Expected space in 2050	
		Conservative	Optimistic
Area (km^2)	1080	14806	24816
Share of Dutch EEZ	2%	25%	42%

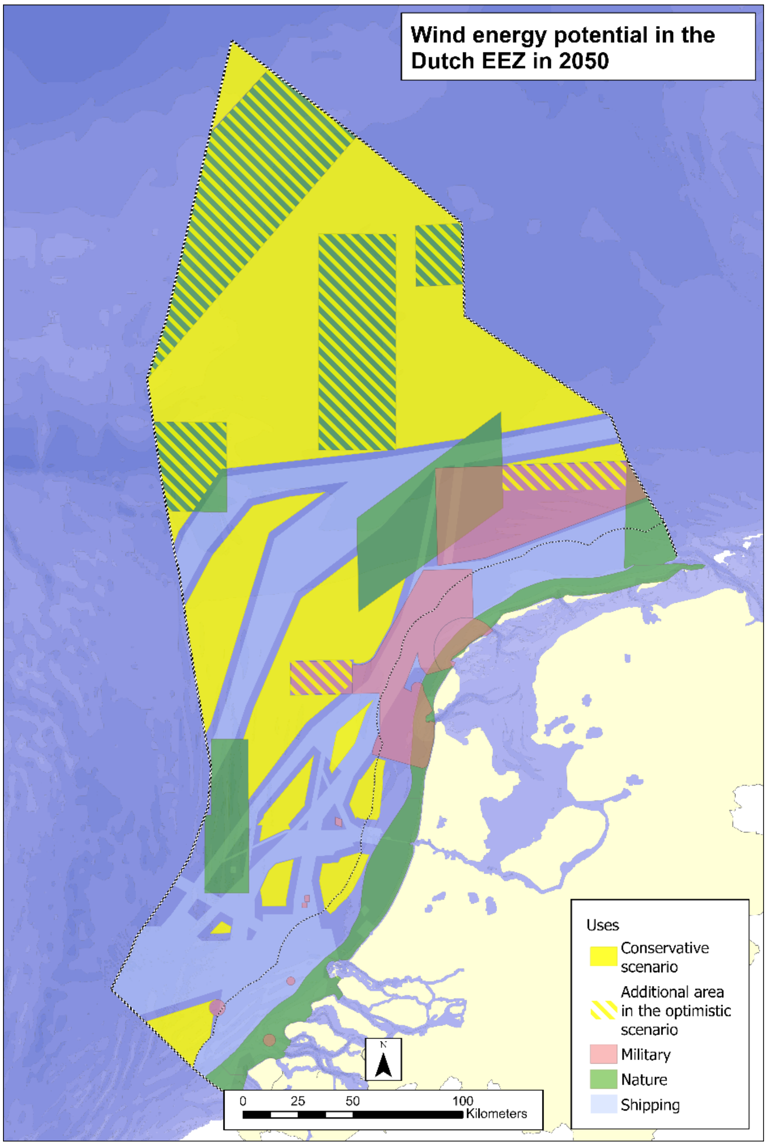

Figure 2 Available space for wind farms in the Dutch EEZ in 2050 in relation to the space used for shipping, nature reserves, and military zones.

While this amount of space for wind farms might be an overestimation, it is important to note that we are trying to put upper bounds on the total wind energy potential in the Dutch EEZ. By determining the maximum capacity that can be placed in a sustainable manner, we can get a clear image of the Dutch dependency on offshore wind energy and can determine which other clean energy sources need to be identified.

To determine the amount of electricity that can be generated in both scenarios, we used the adjusted KEBA model [23], as explained above. To employ the KEBA model, the available space identified was approximated as a large rectangular wind farm with uniform power density. The yellow and green rectangles in Figure 3 represent the conservative and optimistic scenarios, respectively. The rectangles are facing southwest, which is the prevailing wind direction in the Dutch EEZ [42]. The wind farm in the conservative scenario had a width of 135 km and a downwind length of 110 km. In the optimistic scenario, the wind farm was 165 km wide and had a downwind length of 150 km. To calculate the energy yields, a wind speed histogram represented by a Weibull distribution, with a median of 7.4 m/s, $k = 3.1$, and $\lambda = 8.33$, was used. This distribution closely resembles the typical wind speeds in the North Sea at the hub height [27]. Assuming a neutral atmosphere and a surface roughness of 0.0001 (calm open sea), the drag coefficient of 0.0012 and the boundary layer height of 1400 m were determined.

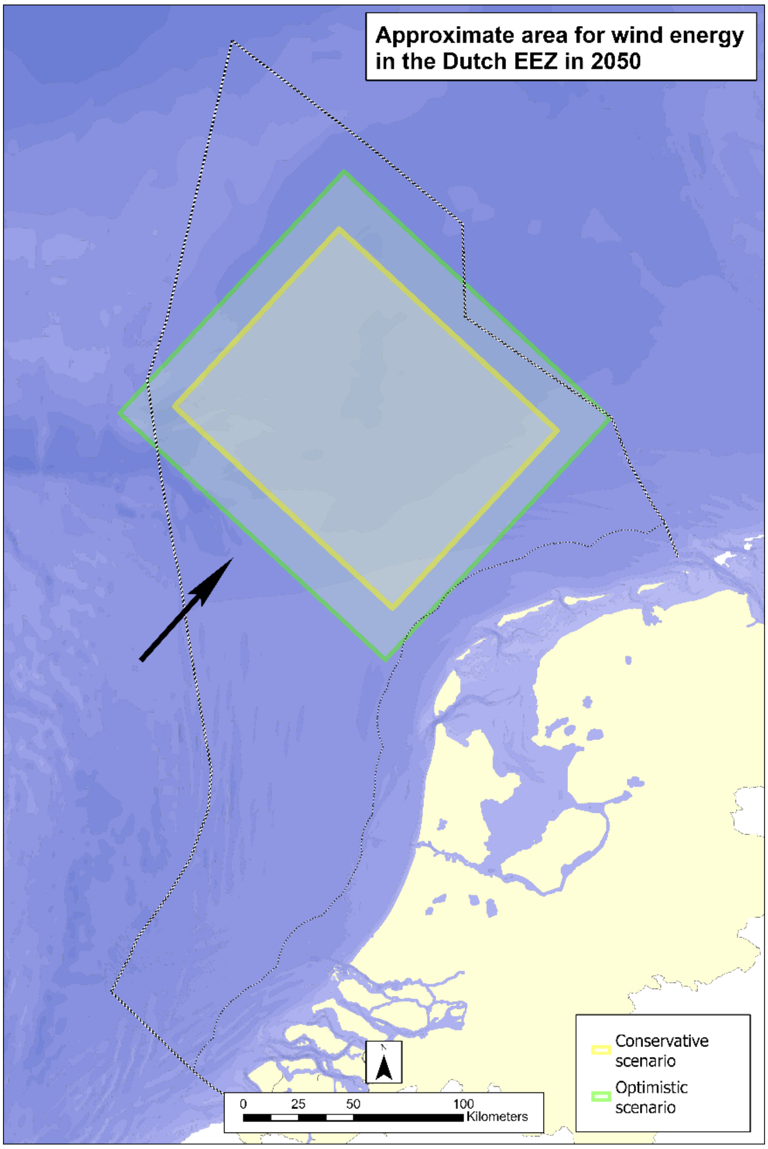

Figure 3 Approximate area for wind energy in the Dutch EEZ in 2050. The yellow rectangle represents the available wind farm area in the conservative scenario. The green rectangle represents the total space that can be realized by co-use in the optimistic scenario. The black arrow shows the prevailing wind direction.

For each of the 10 configurations, the installed capacity, the number of turbines, and thus the downwind spacing was determined. Using these values, the capacity factor of the wind farm was calculated, which gave the total yield.

Table 8 gives the different parameters of the wind farm in the conservative scenario, which correspond to the yellow rectangle in Figure 3. The total surface area of this rectangular farm is 14850 km^2, and depending on the power density, between 15 and 119 GW of installed capacity can be deployed in this area. This corresponds to approximately 1000 to 8500 wind turbines with a rated capacity of 14 MW each. Final power yields range from 69 to 409 TWh/yr. The parameters in the case of the optimistic scenario, corresponding to the green rectangle in Figure 3, are given at the bottom of Table 8. Thanks to the additional areas identified for co-use, the total surface area is 24750 km^2. The total installed capacity that can be deployed in this area ranges from 25 to 198 MW, depending on the power density. This corresponds to approximately 2000 to 14000 wind turbines yielding 113 to 625 TWh/yr.

Table 8 Wind farm parameters for ten distinct power density assumptions.

	Scenario					Results		
	Surface area [km²]	**Power density [MW/km²]**	**Installed capacity [GW]**	**Number of turbines [N]**	**Downwind spacing [rotor diameters]**	**Capacity factor [%]**	**Yield [GW]**	**Yield [TWh/yr]**
Conservative scenario	14850	1	15	1061	17.0	53.0	8	69
	14850	2	30	2121	12.0	50.6	15	132
	14850	4	59	4243	8.5	46.2	27	240
	14850	6	89	6364	6.9	42.5	38	332
	14850	8	119	8486	6.0	39.3	47	409
Optimistic scenario	24750	1	25	1768	17.0	52.2	13	113
	24750	2	50	3536	12.0	49.2	24	213
	24750	4	99	7071	8.5	44.0	44	381
	24750	6	149	10607	6.9	39.6	59	516
	24750	8	198	14143	6.0	36.0	71	625

Figure 4(a) shows the installed and calculated capacity factors for both scenarios. At a power density of 4 MW/km^2, approximately 60 GW and 100 GW can be installed in the conservative and optimistic scenarios, respectively. This figure also shows that at a low power density of 1 MW/km^2, the capacity factor is very similar for the conservative and optimistic scenario at approximately 53%. For higher power densities, and thus a larger number of turbines, the capacity factor drops to roughly 39% and 36%, respectively. The reduction in the capacity factor is non-linearly dependent on the number of wind turbines on the farm. This effect is also seen in Figure 4(b), in which the total yield of each configuration is plotted. A recent study by Gasunie and TenneT estimated the total final Dutch energy use in 2050 at 416 TWh/yr [43]. The electricity demand comprised 35% or 146 TWh of total energy use, whereas the remaining 65% was in the form of molecules such as hydrogen and methane. We used the standard conversion factors for these molecules to input the final electricity demand for the entire Dutch energy system in 2050 at 616 TWh/year. This number was used to plot the yield of the configurations as a percentage of the total Dutch energy use.

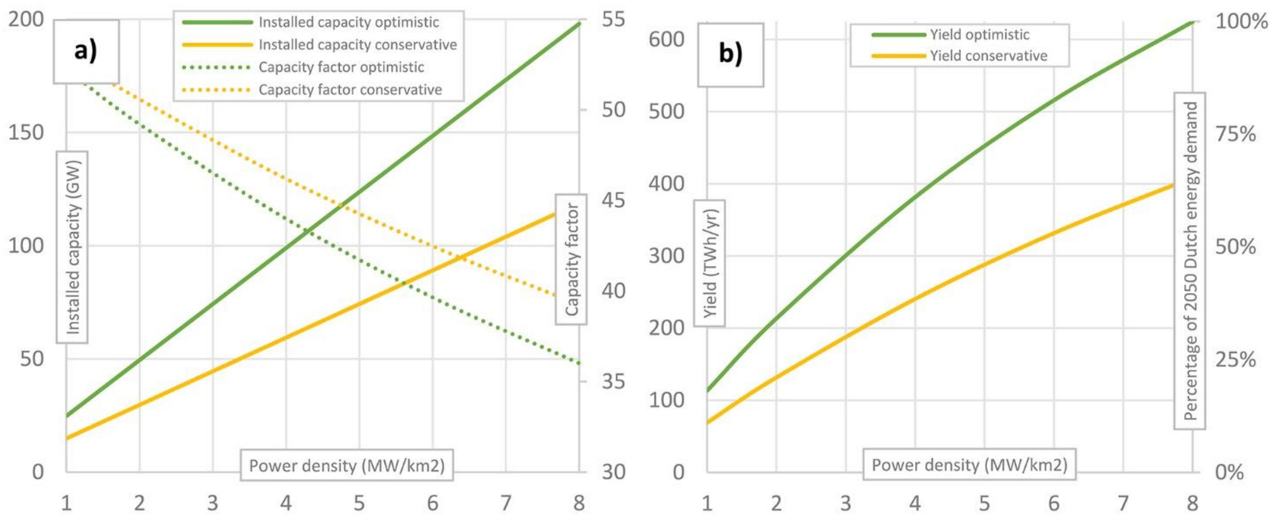

Figure 4 Results for the two main wind farm scenarios in the Dutch EEZ. The yellow lines represent the conservative scenario from Figure 2, whereas the green lines represent the larger wind farm in the optimistic scenario. (a) Installed capacity (solid) and capacity factor (dashed), and (b) yield and yield as a percentage of 2050 Dutch energy demand.

Table 8 and Figure 4 show that the power densities below 4 MW/km^2 do not reach a total installed capacity of 60 GW. In addition, for high power densities, the capacity factor drops below 40%. Lastly, the additional space created by selecting areas for co-use increases the installed capacity by 68% and the total yield from 52% to 64%.

4. Discussion

Having shown the effect of installing wind farms at different power densities on their capacity factor and electricity yield, we are now in a position to identify the overall potential of wind energy in the Dutch EEZ, which is critical for evaluating the possible long-term sustainable electricity production level from wind energy in the North Sea. The offshore wind energy potential can be described at five different levels: the theoretical, physical, economic, environmental, and social potential. In this study, we focus predominantly on the first two types of potentials and leave the other three types for future investigation.

To determine the theoretical potential, we need to identify the atmospheric replenishment rate of kinetic energy. Wind, or the movement of air particles, is caused by differences in the temperature of the atmosphere. By measuring the radiation from the sun and its absorption in the tropics and at the poles, it is possible to determine a heat flux at the planetary scale. Performing this calculation yields a global mean generation rate of the kinetic energy of approximately 2 MW/km^2 [16]. This number matches well with observations in the literature [17-20]. Thus, over large scales, 2 MW/km^2 is assumed to be a reliable approximation for the theoretical potential of wind energy.

The main purpose of our present study is to narrow down the theoretical potential to obtain the physical potential, for which constraints such as shipping lanes, military zones, and nature reserves need to be taken into account since they limit the availability of space for wind farms in the Dutch EEZ. Taking an average power density for the entire Dutch EEZ of 2 MW/km^2 positively leads to a system with sustainable long-term electricity production. However, our conservative and optimistic scenarios contain large areas of open water reserved for shipping lanes, military zones, and nature reserves, which allow for kinetic energy replenishment. In the two scenarios, wind farm locations take up less than half of the total area (25% and 42%, respectively), indicating that the allowable installed power density in those areas can at least be a factor of 2 higher. We, therefore, conclude that wind farms with an installed power density of 4 MW/km^2 in the areas shown in Figure 2 can still lead to a sustainable wind energy system for the Dutch EEZ. In the conservative scenario, only 25% of the Dutch EEZ is reserved for wind farms, which implies that one could argue for an even higher power density of 6 or 8 MW/km^2. However, these higher power densities decrease the capacity factor of the wind farm by approximately 4–7 percentage points in comparison to a wind energy system with a power density of 4 MW/km^2. A lower capacity factor increases the required number of turbines, electricity cables, maintenance activities, and energy storage, which drive up the cost of wind energy [44].

While the economic potential is not explicitly discussed in this study, it might not differ very much from the physical potential that we calculated here, thanks to the shallow waters of the North Sea, the strong winds, and the proximity of this water body to large energy users. These excellent conditions lead to favorable business cases, which increases the economic potential [45]. The environmental potential accounts for the natural impacts of marine activities such as offshore wind farming, notably for seabirds above water and fish and crustacea below the surface of the North Sea. While many studies have already been undertaken in this domain, much is still to be understood (see, e.g., Busch et al., 2013 [46]; Furness et al., 2013 [47]; Dierschke et al., 2016 [48]). The social potential, which accounts for public acceptance and legal concerns, is essential for determining the ultimately installable offshore wind energy capacity. No strong limitations currently seem to exist in this respect. However, the social potential is difficult to accurately project on long time scales [49]. All three additional types of offshore wind energy potentials, namely, economic, environmental, and social, deserve further in-depth research. The physical potential that we have determined for offshore wind power in the Dutch North Sea constitutes an upper bound for the capacity that can realistically be placed in a sustainable manner in the EEZ from an economic, environmental, and social perspective, and thus helps in clarifying the extent to which the Dutch economy could possibly depend on offshore wind energy in the future.

In a new phase of wind energy, in which all North Sea countries are greatly increasing their installed capacity, it is becoming increasingly important to consider the overall effect of installing such systems. Currently, the average installed power density of wind farms in the North Sea is approximately 7 MW/km^2. Continuing to build wind farms at this density will decrease the overall efficiency of offshore wind energy, which drives up the total generation capacity required to meet the energy demands and, therefore, the total costs. In addition, large-scale unsustainable kinetic energy extraction could have climatological effects, such as seasonal winds or regional temperature changes [50, 51]. Additional research from a wide variety of disciplines is required to understand these large-scale effects.

Thus, we used the KEBA model, in a similar approach used for the Dutch EEZ, to obtain a rough estimate of the sustainable wind energy potential on the European scale. The available space was estimated by combining the EEZs of Belgium, Denmark, Germany, the Netherlands, Norway, and the United Kingdom and selecting good wind farm locations within these geographical zones. The selected area was based on the locations of the current and proposed wind farms [52], water depth (maximum ~50 m), and distance from the shore (maximum ~270 km): see the map shown in Figure

5. This gave a surface of 208800 km^2. It should be noted here that this procedure is slightly different from the Dutch case because we did not account for prognoses in shipping lanes, military zones, and nature reserves or their possible future co-use. To estimate the physical wind energy potential, an average power density of 2 MW/km^2 over the entire surface was taken, which is equal to the theoretical replenishment rate. In reality, the wind farms themselves will have a higher power density, and the open space reserved for other uses will allow kinetic energy replenishment. At an average power density of 2 MW/km^2, a total of 418 GW can be installed on the identified North Sea space, corresponding to 29836 turbines of 14 MW each, with a spacing of 12 rotor diameters (12 × 220 m = 2640 m). With a calculated capacity factor of 43.3%, these turbines yield 1584 TWh/yr. In 2050, electricity demand for Europe is estimated to be around 4000 TWh/yr [53]. Thus, these wind farms could provide approximately 40% of the total European electricity demand in 2050.

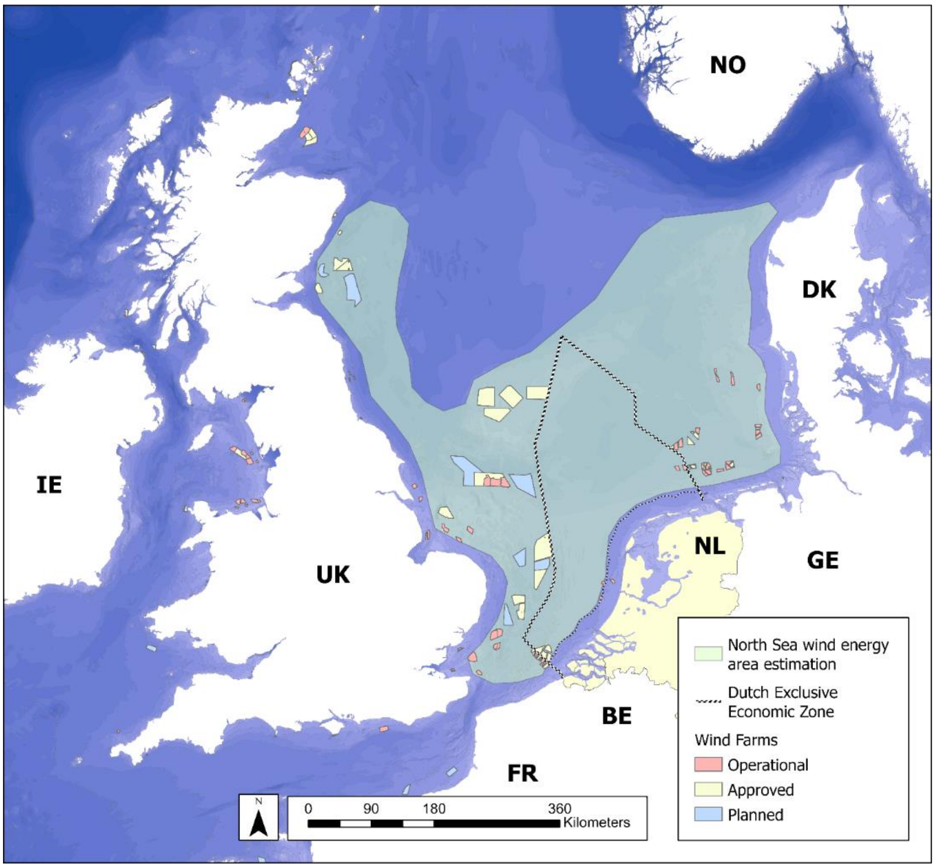

Figure 5 Combined estimated wind farm area for the North Sea countries.

Lastly, a recent study tried to determine the effect of low-level jets on turbine efficiency in wind farms [54]. In the North Sea, these localized gusts of wind are observed approximately 8% of the time. Depending on their height relative to the nacelle of the turbine, they can create a positive or negative shearing effect, which transports kinetic energy downward or upward, respectively, into the wind farm. This additional vertical kinetic energy flux can enhance the electricity output of the downwind turbines. Calculations have shown that this benefit can be exploited by selecting a turbine spacing of approximately 7 rotor diameters, which increases for larger wind farms [54]. While these findings have not yet been broadly recognized in the wind energy community and need additional research, the effects of low-level jets could increase the electricity yield of the proposed large-scale wind farms.

5. Conclusion

The Dutch EEZ in the North Sea is a unique location for offshore wind energy. Its shallow waters and strong winds provide a large wind energy potential as well as low potential electricity generation costs. The proximity of large industrial clusters implies a large demand for electricity, which helps the cost-effective operation of large offshore wind parks. In order to ensure the longevity of wind power, careful consideration must be given to the power density of the installed wind farms to not exceed the atmospheric kinetic energy replenishment rates.

From this study, we concluded that installing wind farms in the Dutch EEZ with a power density of up to 4 MW/km^2 can provide long-term electricity from wind power without major efficiency losses. While the atmospheric replenishment rate of kinetic energy was determined at 2 MW/km^2, we conclude that in the case of the Dutch North Sea, enough space between wind farms is reserved for shipping lanes, military zones, and nature reserves to sufficiently allow for kinetic energy replenishment.

We found that by installing wind farms at a power density of 4 MW/km^2 and using only the readily available area in 2050, the Dutch EEZ can host up to 59 GW of installed capacity. We determine a capacity factor of 46%, with which these turbines yield a total amount of electricity of 240 TWh/yr. This accounts for 165% of the projected Dutch electricity use in 2050 (39% of the final energy use). By selecting nature reserves for co-use and decreasing the size of military zones, the installed capacity can be increased to 99 GW, yielding 381 TWh/yr with a capacity factor of 44%. This accounts for 262% of projected Dutch electricity use in 2050 (62% of final energy use).

By extending our calculation to a European scale, we concluded that the North Sea could sustainably host 418 GW of installed wind power capacity. At a capacity factor of 43%, this wind energy capacity can yield 1584 TWh/yr, accounting for 40% of projected European electricity demand in 2050.

Acknowledgments

The authors would like to thank their colleagues at TNO, especially Bernard Bulder, Edwin Bot, and Jan Willem Wagenaar, for valueable support in enabling and improving our analysis. The research that allowed the publication of this paper has been undertaken with financial support from the Ministry of Economic Affairs and Climate Policy of the Netherlands.

Author Contributions

FT developed the paper’s concept, structured the data, researched the literature and performed the calculations through the KEBA model. FT and BvdZ designed the scenarios and determined which results to show. FT wrote the majority of the text through the guidance of BvdZ. BvdZ helped structure the manuscript and reviewed the text many times. FT handled the review process.

Competing Interests

The authors declare no competing financial interests.

References

1. Paris agreement to the united nations framework convention on climate change. Proceedings of COP-21; 2015 November 30-December 11; Paris, France. Bonn: The secretariat of the United Nations Framework Convention on Climate Change.
2. IPCC. Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In Press; 2018.
3. IEA. World energy outlook 2021 [Internet]. Paris: IEA; 2021. Available from: https://www.iea.org/reports/world-energy-outlook-2021.
4. Energieopwek.nl. Inzicht in de actuele (near-realtime) opwekking van duurzame energie in Nederland [Internet]. Energieopwek.nl; 2021 [cited date 2021 October 11th]. Available from: https://energieopwek.nl/.
5. Netherlands Environmental Assessment Agency. Klimaat-en energieverkenning 2020 [Internet]. The Hague: Netherlands Environmental Assessment Agency; 2020. Available from: https://open.overheid.nl/repository/ronl-6a042d8f-41f5-4275-a733-52223ca41cd6/1/pdf/Klimaat-%20en%20energieverkenning%202020.pdf.
6. Noordzeeloket. Functions and use [Internet]. Noordzeeloket; 2021 [cited date 2022 August 4th]. Available from: https://www.noordzeeloket.nl/en/functions-and-use/.
7. Ministry of Economic Affairs and Climate Policy. Letter to parliament: Offshore wind energy roadmap 2030 [Internet]. The Hague: Ministry of Economic Affairs and Climate Policy; 2018. Available from: https://english.rvo.nl/sites/default/files/2018/03/Letter-Parliament-Offshore-Wind-Energy-2030.pdf.
8. Ministry of Infrastructure and Water Management. Aanvullend ontwerp programma noordzee 2022-2027 [Internet]. The Hague: Ministry of Infrastructure and Water Management; 2021. Available from: https://open.overheid.nl/repository/ronl-72c2fa9b-963c-4b28-a058-ecdf9254c043/1/pdf/bijlage-aanvullend-ontwerp-programma-noordzee-2022-2027.pdf.
9. Dutch Ministry of Economic Affairs and Climate Policy. Verkenning aanlanding wind op zee (VAWOZ) [Internet]. The Hague: Dutch Ministry of Economic Affairs and Climate Policy; 2021. Available from: https://www.rvo.nl/onderwerpen/bureau-energieprojecten/lopende-projecten/vawoz.
10. Dutch Central Government. Nieuwsbericht: Kabinet verdubbelt productie windenergie op zee [Internet]. The Hague: Dutch Central Government; 2022 [cited date 2022 March 27th]. Available from: https://www.rijksoverheid.nl/actueel/nieuws/2022/03/18/kabinet-verdubbelt-productie-windenergie-op-zee.
11. DNV-GL. Noordzee energie outlook [Internet]. Oslo: DNV-GL; 2020. Available from: https://www.vemw.nl/l/library/download/urn:uuid:fa883837-9d05-49ba-a120-838036652130/2020-09-00+dnv-gl+noordzee+energy+outlook.pdf?format=save_to_disk.
12. Berenschot/Kalavasta. Klimaatneutrale energiescenario's 2050 [Internet]. Amsterdam: Berenschot/Kalavasta; 2020. Available from: https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2020/03/31/klimaatneutrale-energiescenarios-2050/Rapport-Klimaatneutrale-energiescenarios-2050.PDF.

13. Miller LM, Brunsell NA, Mechem DB, Gans F, Monaghan AJ, Vautard R, et al. Two methods for estimating limits to large-scale wind power generation. Proc Natl Acad Sci U S A. 2015; 112: 11169-11174.
14. Jacobson M, Archer C. Saturation wind power potential and its implications for wind energy. Proc Natl Acad Sci U S A. 2012; 109: 15679-15684.
15. WindEurope. Offshore Wind in Europe: Key trends and statistics 2020 [Internet]. Brussels: WindEurope; 2021. Available from: https://windeurope.org/intelligence-platform/product/offshore-wind-in-europe-key-trends-and-statistics-2020/.
16. Kleidon A. Physical limits of wind energy within the atmosphere and its use as renewable energy: From the theoretical basis to practical implications. Meteorol Zeitschrift. 2021; 30: 203-225.
17. Possner A, Caldeira K. Geophysical potential for wind energy over the open oceans. Proc Natl Acad Sci U S A. 2017; 114: 11338-11343.
18. Boer G, Lambert S. The energy cycle in atmospheric models. Clim Dyn. 2007; 30: 371-390.
19. Li L, Ingersoll A, Jiang X, Feldman D, Yung Y. Lorenz energy cycle of the global atmosphere based on reanalysis datasets. Geophys Res Lett. 2007; 34. doi:10.1029/2007gl029985.
20. Lettau H. A study of the mass, momentum and energy budget of the atmosphere. Arch Meteorol Geophys Bioklimatol Ser A. 1954; 7: 133-157.
21. Netherlands Environmental Assessment Agency. The future of the North Sea [Internet]. The Hague: Netherlands Environmental Assessment Agency; 2018. Available from: https://www.noordzeeloket.nl/publish/pages/160294/pbl-2018-the-future-of-the-north-sea.pdf.
22. WindEurope. Our energy, our future [Internet]. Brussels: WindEurope; 2019. Available from: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf.
23. Kleidon A, Miller L. The Kinetic Energy Budget of the Atmosphere (KEBA) model 1.0: A simple yet physical approach for estimating regional wind energy resource potentials that includes the kinetic energy removal effect by wind turbines. Geosci Model Dev. 2020; 13: 4993-5005.
24. Rijkswaterstaat. ArcGIS REST services directory [Internet]. Utrecht: Rijkswaterstaat; 2021 [cited date 2022 August 4th]. Available from: https://geoservices.rijkswaterstaat.nl/arcgis2/rest/services/GDR.
25. MMM: Mesoscale & Microscale Meteorology Laboratory. Weather research & forecasting model (WRF) [Internet]. Boulder, CO: Mesoscale & Microscale Meteorology Laboratory; 2021 [cited date 2022 April 11th]. Available from: https://www.mmm.ucar.edu/weather-research-and-forecasting-model.
26. Kumar R, Stallard T, Stansby P. Large-scale offshore wind energy installation in northwest India: Assessment of wind resource using Weather Research and Forecasting and levelized cost of energy. Wind Energy. 2020; 24: 174-192.
27. Volker P, Hahmann A, Badger J, Jørgensen. Prospects for generating electricity by large onshore and offshore wind farms. Environ Res Lett. 2017; 12: 034022.
28. GE Renewable Energy. Haliade-X offshore wind turbine [Internet]. GE Renewable Energy; 2020 [cited date 2021 July 6th]. Available from: https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine.

29. Rijkswaterstaat. Scheepvaartreglement territoriale zee [Internet]. Utrecht: Rijkswaterstaat; 2018 [cited date 2022 March 27th]. Available from: https://wetten.overheid.nl/BWBR0042533/2018-05-01.
30. Netherlands Enterprise Agency. Helicopter accessibility new designated wind farm zones. Utrecht: Netherlands Enterprise Agency; 2018; RVO.nl: WOZ2170048.
31. IMARES. Aanvullende beschermende gebieden op de Noordzee. Wageningen: IMARES; 2012; no. C154/12.
32. Vogelbescherming.nl. Zeevogel-eldorado Bruine Bank wordt toch Natura 2000-gebied [Internet]. Vogelbescherming.nl; 2020 [cited date 2020 November 8th]. Available from: https://www.vogelbescherming.nl/actueel/bericht/zeevogel-eldorado-bruine-bank-wordt-natura-2000-gebied.
33. Segeren M. Gentle driving of piles (GDP) [Internet]. Utrecht: GROW Offshore Wind; 2019 [cited date 2020 February 9th]. Available from: https://grow-offshorewind.nl/project/gentle-driving-of-piles.
34. Dutch Physical Environment Consultative Council. Het akkoord voor de noordzee [Internet]. The Hague: Dutch Physical Environment Consultative Council; 2020. Available from: https://www.noordzeeloket.nl/publish/pages/180789/onderhandelaarsakkoord_voor_de_noordzee_juni_2020.pdf.
35. Rozemeijer M, Wolfshaar K. Desktop study on autecology and productivity of European lobster (Homarus Gammarus, L) in offshore wind farms. Wageningen: Wageningen Marine Research; 2019; no. C109/18.
36. Tonk L, Rozemeijer M. Ecology of the brown crab (cancer pagurus) and production potential for passive fisheries in dutch offshore wind farms. Wageningen: Wageningen Marine Research; 2019; no. C064/19A.
37. Smaal A, Kamermans P, Kleissen F, van Duren L, van der Have T. Flat oysters on offshore wind farms: Opportunities for the development of flat oyster populations on existing and planned wind farms in the Dutch section of the North Sea. Wageningen: Wageningen Marine Research; 2017; no. C052/17.
38. Dutch Ministry of Infrastructure and Water Management. Ontwerp programma noordzee 2022-2027 [Internet]. The Hague: Dutch Ministry of Infrastructure and Water Management; 2021. Available from: https://open.overheid.nl/repository/ronl-b28d8bb1-3b31-4f83-8cf8-bbeddf862186/1/pdf/4-ontwerp-programma-noordzee-2022-2027.pdf.
39. Dutch Ministry of Infrastructure and Water Management. Beleid en Regelgeving Informatiesysteem Noordzee (BREIN)-Herziening 2020 [Internet]. Utrecht: Dutch Ministry of Infrastructure and Water Management; 2020. Available from: https://puc.overheid.nl/rijkswaterstaat/doc/PUC_628490_31/.
40. Witteveen+Bos. Cost evaluation of North Sea offshore wind post 2030. Deventer: Witteveen+Bos; 2019; 112522.
41. European Wind Energy Association. Deep water [Internet]. Brussels: European Wind Energy Association; 2013. Available from: http://www.ewea.org/fileadmin/files/library/publications/reports/Deep_Water.pdf.
42. The Royal Netherlands Meteorological Institute. The Dutch offshore wind atlas (DOWA). De Bilt: The Royal Netherlands Meteorological Institute; 2019; TR-380.

43. Gasunie/TenneT. Infrastructure outlook 2050 [Internet]. Groningen: Gasunie/TenneT; 2019. Available from: https://www.gasunie.nl/en/expertise/energy-system/infrastructure-outlook-2050.
44. Stevens R. Dependence of optimal wind turbine spacing on wind farm length. Wind Energy. 2015; 19: 651-663.
45. LeanWind. Driving cost reductions in offshore wind [Internet]. LeanWind; 2017. Available from: https://windeurope.org/wp-content/uploads/files/about-wind/reports/LEANWIND-Driving-cost-reductions-in-offshore.pdf.
46. Busch M, Kannen A, Garthe S, Jessopp M. Consequences of a cumulative perspective on marine environmental impacts: Offshore wind farming and seabirds at North Sea scale in context of the EU marine strategy framework directive. Ocean Coast Manag. 2013; 71: 213-224.
47. Furness R, Wade H, Masden E. Assessing vulnerability of marine bird populations to offshore wind farms. J Environ Manage. 2013; 119: 56-66.
48. Dierschke V, Furness R, Garthe S. Seabirds and offshore wind farms in European waters: Avoidance and attraction. Biol Conserv. 2016; 202: 59-68.
49. Dutch Central Government. Kamerstuk 34058, nr. 3 Wet windenergie op zee [Internet]. Dutch Central Government; 2014 [cited date 2022 March 27th]. Available from: https://zoek.officielebekendmakingen.nl/kst-34058-3.html.
50. Miller L, Keith D. Climatic impacts of wind power. Joule. 2018; 2: 2618-2632.
51. Keith DW, DeCarolis JF, Denkenberger DC, Lenschow DH, Malyshev SL, Pacala S, et al. The influence of large-scale wind power on global climate. Proc Natl Acad Sci U S A. 2004; 101: 16115-16120.
52. The European Marine Observation and Data Network-Humanactivities. EU wind farm GIS database. Wind farms (polygons) [Internet]. Ostend: The European Marine Observation and Data Network; 2021 [cited date 2021 November 16th]. Available from: https://www.emodnet-humanactivities.eu/search-results.php?dataname=Wind+Farms+(Polygons).
53. Kustova I, Egenhofer C. The EU electricity sector will need reform, again. Intereconomics. 2019; 54: 332-338.
54. Gadde S, Stevens R. Effect of low-level jet height on wind farm performance. J Renew Sustain Energy. 2021; 13: 013305.