MARINE ENERGY IN THE DUTCH NORTH SEA

Potential benefits to the Dutch energy system

WHITE PAPER

CONTENTS

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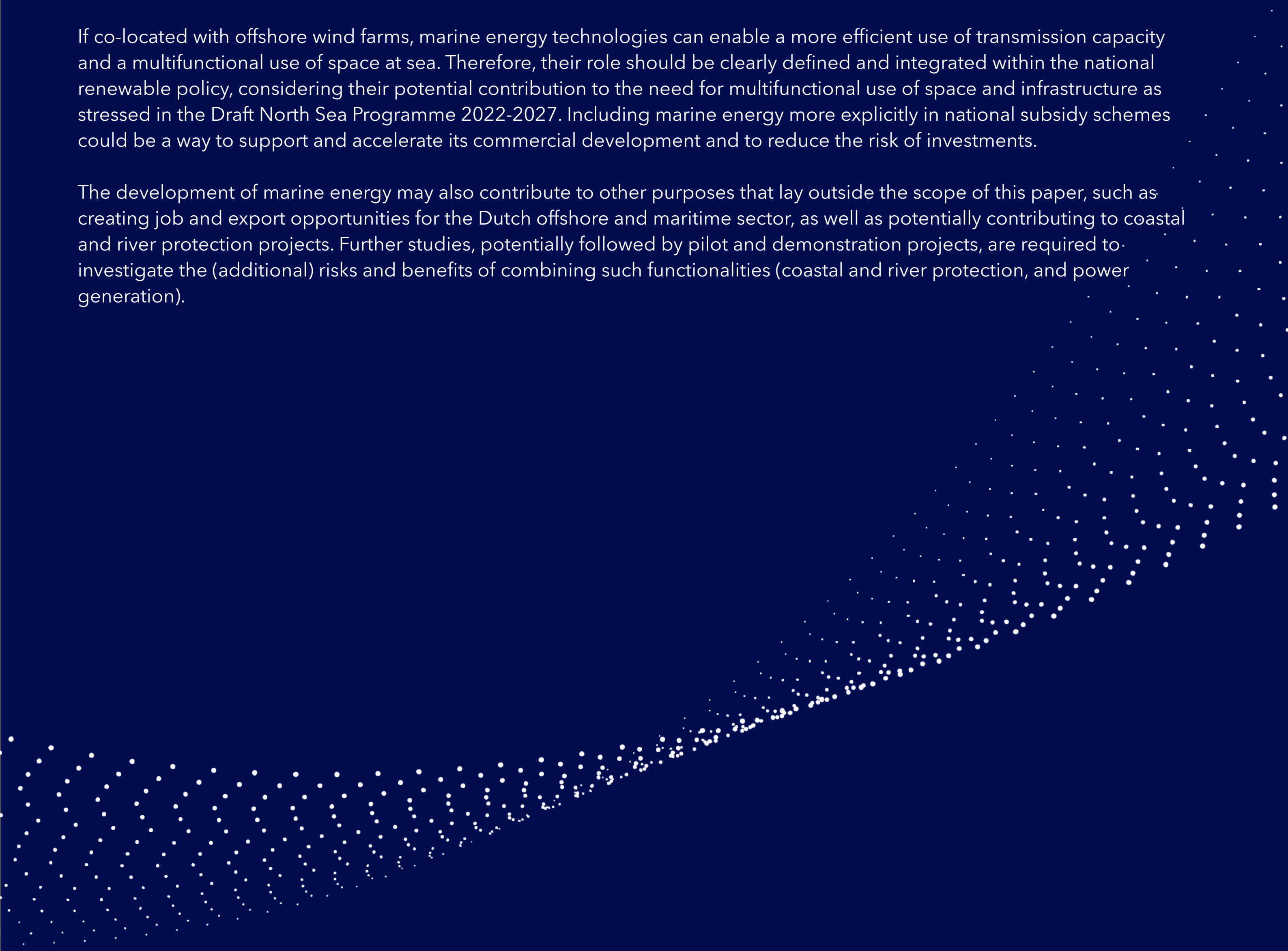
EXECUTIVE SUMMARY

Marine energy has been gaining attention as a potential contributor to the diversification of the Dutch renewable portfolio and to sustainable energy generation in the North Sea. In July of this year, three motions[1] were submitted to the Dutch Parliament, requesting the government to invest in research and demonstrations of marine energy. All three were accepted, indicating the willingness of a majority of the Dutch Parliament to further explore the development and deployment of marine energy in the Netherlands.

Thanks to their CO_2-free and reliable nature, marine energy technologies may play a role in bulk power generation, balancing of the grid, and the optimization of generation portfolios. Wave energy and tidal energy are currently the most promising technologies to harness the power of the North Sea, whereas salinity gradient technologies may be used in any body of water with a difference in salt concentration, such as in river mouths, where fresh water is discharged at sea, or where the water of the IJsselmeer connects with the Waddenzee.

If co-located with offshore wind farms, marine energy technologies can enable a more efficient use of transmission capacity and a multifunctional use of space at sea. Therefore, their role should be clearly defined and integrated within the national renewable policy, considering their potential contribution to the need for multifunctional use of space and infrastructure as stressed in the Draft North Sea Programme 2022-2027. Including marine energy more explicitly in national subsidy schemes could be a way to support and accelerate its commercial development and to reduce the risk of investments.

The development of marine energy may also contribute to other purposes that lay outside the scope of this paper, such as creating job and export opportunities for the Dutch offshore and maritime sector, as well as potentially contributing to coastal and river protection projects. Further studies, potentially followed by pilot and demonstration projects, are required to investigate the (additional) risks and benefits of combining such functionalities (coastal and river protection, and power generation).



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[1] Motions number 787 (Van der Lee), 793 (Grinwis and Stoffer) and 797 (Stoffer), July 2021

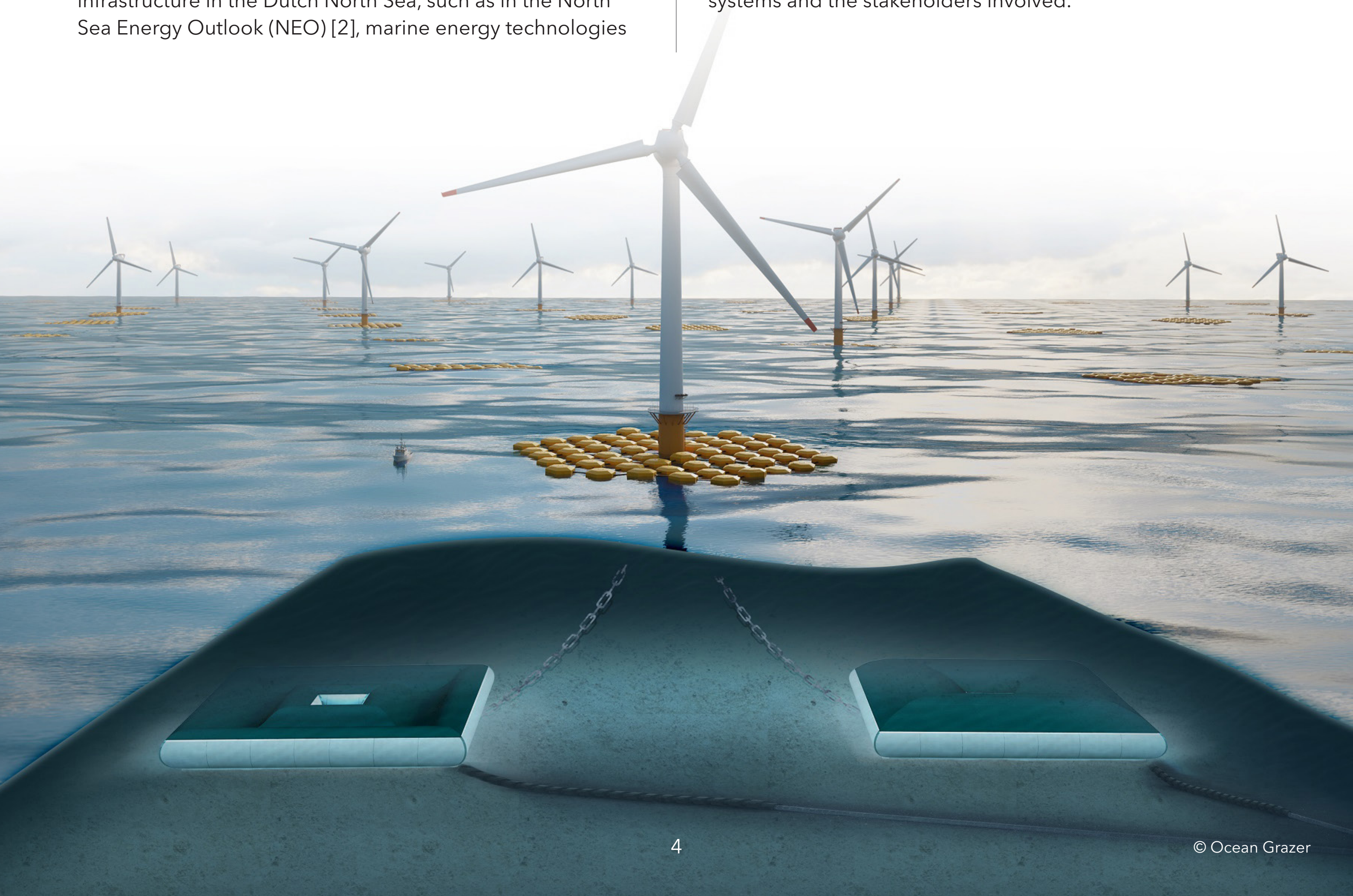
Introduction

The recent IRENA publication *'Offshore Renewables: An action agenda for deployment'* [1] states that '(in) an energy transition scenario aligned with the Paris Agreement target to keep the average global temperature rise below 1.5°C, IRENA's analysis indicated that an offshore wind cumulative installed capacity of more than 380 GW by 2030 and more than 2,000 GW can be deployed globally.' The same analysis projects that ocean energy technologies could reach an installed capacity of around 70 GW by 2030 and 350 GW by 2050 globally.

Offshore wind is expected to make up the majority of the electricity in the Netherlands in the period 2030-2050 [2]. Incremental innovation has made and will continue to make an important contribution to the cost reduction of offshore wind, hence promoting its expansion capacity. Yet, reaching the expected capacity of 38 GW or 72 GW of offshore wind by 2050 requires a faster growth than currently achieved and planned for the 2020-2030 period [3]. At the same time, the strong growth of renewable energy and in particular offshore wind will lead to constraints with respect to costs, space and environmental impact of the required infrastructure, grid capacity, and balancing of supply and demand.

In the current outlooks for development of energy infrastructure in the Dutch North Sea, such as in the North Sea Energy Outlook (NEO) [2], marine energy technologies are not included, especially due to previously assumed limited capacity potentials. These innovative technologies, however, could play a key role in fostering system integration, enabling a multipurpose use of the zones occupied by wind farms and increasing the efficiency of the available infrastructure due to a less variable and fluctuating production profile. In this light, the Dutch Marine Energy Centre (DMEC) requested DNV to reflect upon the role(s) marine energy could play, and the benefits that it can bring to the Dutch energy system.

This paper provides an overview of the most promising marine energy technologies for the Dutch North Sea and highlights the potential benefits for the Dutch energy systems and the stakeholders involved.



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Scope of the paper

The marine energy technologies described in this paper are the following: energy from salinity gradient, energy from tides, and energy from waves. Various companies in the Netherlands are working on the development of these techologies.

Although DNV recognizes that there are more technologies available, DNV limits the scope to these technologies under development in the Netherlands. A brief overview is available in the Appendix. Recommendations are partly based on the characteristics of the described marine energy technologies. As for the geographical scope, this paper focuses on the Dutch North Sea and the coastal areas featuring a fresh-salt water interface.

The Dutch part of the North Sea is approximately 57,500 km^2, which is shared among all water-based activities, such as shipping, defense, sand extraction, nature conservation, food production (fishing), and offshore wind energy. The areas designated for the generation of offshore wind energy until 2027 have been proposed in the Draft North Sea Programme 2022-2027 and are currently under review [4]. The document stresses the increasing need of a multifunctional use of the space and of the wind energy areas, such as for the generation of sustainable energy from other innovative technologies.

The Netherlands also encompasses the Waddenzee (approximately 2,400 km^2), the IJsselmeer (1,100 km^2), the Zuidwestelijke Delta, and the Eems-Dollard, where fresh waters meet the sea. All these areas are managed by Rijkswaterstaat (the Directorate General for Public Works and Water Management).

Other water bodies, such as rivers, streams, and lakes under regional authorities, fall outside the geographical scope of this paper.

The sources used during the preparation of this paper were chosen based on their credibility and recent publication date (if possible, no older than three years). It was noted that, owning to a scarcity of recent independent studies, the literature available on the marine energy potential in the Netherlands is limited and tends to refer to the same data from the early 2000, some of which might be based on outdated assumptions. DNV strived for reporting the most recent estimates, based on the characteristics of the latest marine energy technologies.

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Roles and advantages of marine energy technologies

The most common utility-scale renewable energy sources are wind and sun. After many years of public funding, these technologies are today the cheapest sources of power generation in the Netherlands. Yet, while the costs of these technologies are decreasing steadily, the problem of their varying nature remains, hence requiring the support of "firm" generation from high-carbon sources, such as gas and coal, or from batteries with limited storage capacity in comparison to overall system needs. Marine energy technologies provide CO_2-free and reliable energy, as energy is harnessed from stable and predictable phenomena.

The main potential benefits offered to the Dutch power energy system by the investigated technologies are the following:

1. Salinity plants can potentially operate continuously, at least for 8,000 full-load hours per year, hence providing CO_2- free and renewable baseload power. The salt concentration difference between fresh and salt water is indeed a constant characteristic of locations where freshwater discharges into the sea. With an estimated technical potential of 6 TWh per year [5], salinity plants could supply up to 5% of the annual Dutch electricity consumption without emitting CO_2.
2. Tides are fully predictable phenomena, both on the long and the short term. They are consistently available and independent from weather variability. Tidal energy technologies represent a valuable option for portfolio optimization of renewable energy assets. Additionally, they are complementary sources to offshore wind and could provide balancing benefits for the electricity system [6].
3. Waves show a (partly) complementary generation profile with offshore wind in the North Sea [7]. Therefore, wave energy technologies could contribute to portfolio optimization of renewable energy assets. Based on recent calculations from the marine energy sector (see text box below), it would be possible to co-locate wave energy converters within the sea areas designated for offshore wind farms, potentially generating up to 2.6 TWh per year.
4. As both tides [6] and waves [7] show (partly) complementary generation profiles with offshore wind, their integration in the North Sea renewable energy mix could increase the renewable energy production capacity per square kilometer. Likewise, this can help wind farm owners in stabilizing their income as marine energy technologies can keep generating when the wind does not blow.
5. Cable pooling with offshore wind farms can help to optimize the use of transmission infrastructure, resulting in significant cost savings potential for co-located projects [2].
6. In future integrated offshore hubs, marine energy could also provide a more consistent source of electricity for electrolyzers, hence increasing their total number of full-load hours to generate hydrogen.

Several parties can benefit from the development and integration of marine energy technologies in the North Sea. Wind farm operators can optimize their portfolio and hedge their market risks by using marine energy technologies for providing balancing services and by capturing price peaks at moments when the wind does not blow. Therefore, marine energy can provide a means to generate a more diversified and steadier source of income for wind farms' stakeholders. The potential for both tidal and wave energy could be larger if considering other infrastructures like oil & gas platforms and coastal defense works as well. As the national water manager, Rijkswaterstaat, can play a central role in the development of marine energy technologies as a licensing authority, but also as a launching customer and a regional partner for innovation projects [5], [8]. As a bulk renewable source, marine energy can contribute to Rijkswaterstaat's sustainability goals. Another benefit for Rijkswaterstaat may be the possible contribution of marine energy technologies to coastal protection. A combination of both coastal protection and power generation can help to optimize the development of protective infrastructure, although the additional risks and benefits need to be further investigated.

The North Sea Policy Document 2016-2021 and the Draft North Sea Programme 2022-2027 designate the areas where wind farms will be developed by 2029 (see Figure 1) and then expanded by 2050 (see Figure 2), respectively. It is anticipated that offshore wind farms will generate 170 to 325 TWh per year by 2050 [2]. Based on these areas, the marine energy sector expects that, by co-locating suitable wave and tidal technologies in wind farms, it is possible to generate 0.6 TWh per year of CO_2-free electricity in 2030, of which 0.2 TWh per year from tidal systems in Borssele and 0.4 TWh per year from wave systems.

In 2050, the potential marine energy generation within wind farms at the Dutch North Sea is expected to reach up to 2.8 TWh per year. This estimate is calculated based on the assumption that wave technologies may be located either at the edge of the wind farm areas or between the first and second row of wind turbines, assuming an average distance between devices of 0.2 km. The orange segments in Figure 1 and Figure 2 show the possible locations of wave devices, each segment representing approximately 25 km. Tidal kites could be installed directly at the monopiles. In both cases, no additional space would be needed, according to the marine energy sector. Further independent research is required to assess the possibilities in terms of co-location of technologies and sharing of the infrastructure, which would help to improve the perspectives for large-scale commercial deployment of marine energy.

As tidal and waves are (partly) complementary to wind [6], [7], the co-location of marine energy technologies with offshore wind turbines could help to optimize the use of transmission infrastructure and give wind farm owners an alternative resource to stabilize their income. The potential for both tidal and wave energy could be larger if considering other infrastructures like oil & gas platforms and coastal defense works as well.

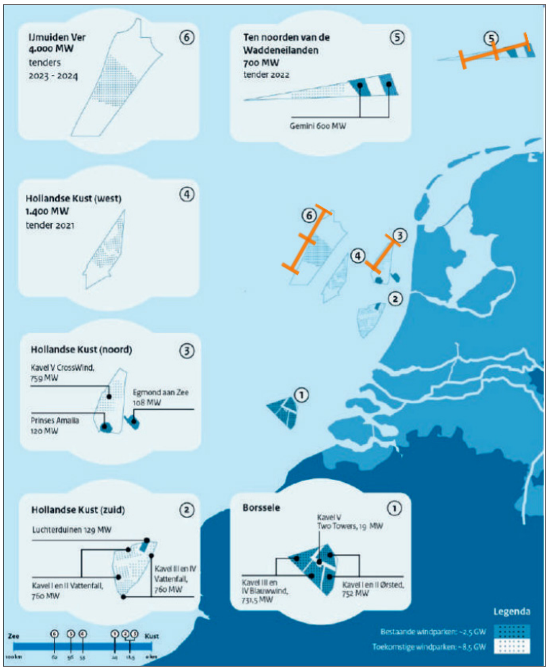

Figure 1 - Wind farm areas by 2029, with assumed row of wave devices. Each orange segment corresponds to 25 km.

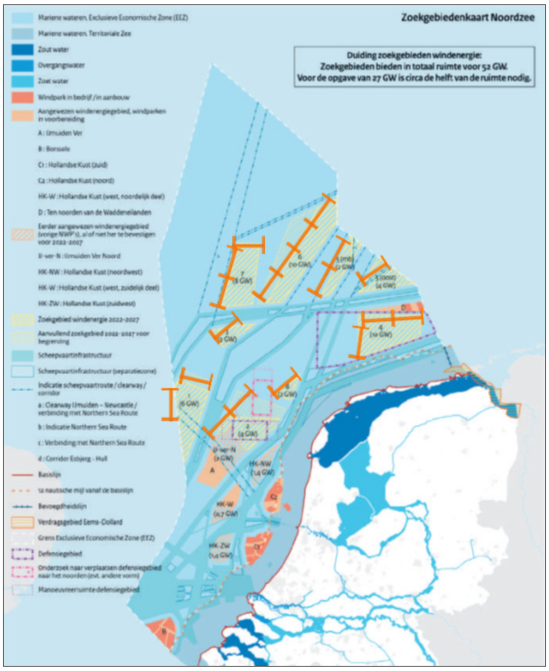

Figure 2 - Wind farm search areas by 2050, with assumed rows of wave devices. Each orange segment corresponds to 25 km.

Current challenges

Pre-commercial technological maturity and uncertain potential capacity are the main obstacles to be overcome by marine energy from waves, tides, and salinity gradient in the short term.

Due to these short-term challenges, these technologies have little potential to significantly contribute to the 2030 national target for renewable power generation [2], [5].
As grid connections for offshore marine energy are not catered for by society through Transmission System Operator (TSO) investments (as with offshore wind, for example), the additionally required infrastructure investments to connect marine technologies are an important cost challenge as well for investors in these technologies.

Yet, if co-location of marine technologies within offshore wind areas is proven possible and cable pooling is permitted, salinity gradient energy, tidal range and current energy, and wave energy can improve their economic and technical feasibility and start to contribute to the national energy mix between 2030 and 2050 [5]. Based on current estimates (see Appendix for a detailed overview of marine energy potential in the Netherlands), these technologies have a total technical potential[2] of 9.15 TWh[3,4] per year, roughly 8% of the current Dutch electricity consumption[5]. Dynamic Tidal Power (DTP) has the greatest potential. However, it is still in a concept phase, so this potential is not considered in the above estimate [2], [9].

Costs of offshore wind in the Dutch North Sea are estimated at 0.04-0.05 €/kWh in 2030 and 0.03 €/kWh in 2050, given particularly favorable conditions [1]. Most optimistic visions estimate in 2030 the salinity gradient energy costs at 0.10-0.15 €/kWh [4], tidal range at 0.09-0.14 €/kWh, based on the Brouwersdam business case [4], tidal current at 0.10-0.27 €/kWh [8], and wave energy at 0.13-0.35 €/kWh [8]. In 2050, costs may fall to 0.05 €/kWh for salinity gradient [4], to 0.06-0.20 €/kWh for tidal current, and to 0.08-0.28 €/kWh for wave energy [8][6]. Wide cost ranges are due to uncertainty in the learning curves, the actual potential in the North Sea, and the globally installed capacity from which Dutch developers would benefit [8].
However, these relatively high-cost ranges and accompanying uncertainties about their potential also initially affected things like solar PV, wind power and grid-scale batteries. These are all technologies that have matured over the past two decades and that have shown (wind and solar) or are showing (batteries) very rapid cost declines, partially thanks to steady policies (targets for technology implementation) and subsidies throughout the globe. Between 2015 and 2018, the costs of tidal technologies already showed a reduction of 40% [10].
Like with solar PV, wind power and batteries, marine energy technologies have deployment potential all over the globe, where they could be deployed as clean sources of long-term predictable generation that help to provide solutions for the challenge of variable output from solar and wind power technologies.

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[2] In this paper, technical potential is used to indicate what is feasible without a significant impact on the already existing infrastructure, without taking economic feasibility into account.

[3] Developers of marine energy technologies provided higher estimates for 2050: tidal stream with kite technology is expected to reach at least 250 MW in capacity and 3,000-5,000 full-load hours operation (1 TWh/year); salinity gradient with RED is estimated at 1,750 MW and 8,600 full-load hours operation (15 TWh/year); wave energy at 5 TWh/year or more; tidal turbines at 300 MW and 2500 full-load hours (0.75 TWh/year). In summary, the total potential would be approximately 22 TWh per year. In literature, on the other hand, the salinity gradient potential is estimated at 6 TWh/year; tidal barrage at 0.1 TWh/year and tidal stream at 0.25 TWh/year. From recent calculations of the marine energy sector (see text box), the wave potential within wind farms is estimated at 2.6 TWh/year, and the tidal stream kite at 0.2 TWh/year. In summary, the total potential would be 9.15 TWh/year. Given the large difference in estimates, we consider 9.15 TWh/year as the more realistic figure for potential development in the Netherlands.

[4] DNV considers only the potential of co-locating wave devices with wind farms, as we consider the potential coming from a line of wave devices along the coast (as mentioned in [15] and [16]) to be more theoretic rather than technical potential.

[5] The electricity consumption in the Netherlands was 113 TWh in 2019 and 111 TWh in 2020 [19].

[6] For the sake of consistency, tidal and wave costs based on the JRC study [20] and the SDE++ [17] are reported.

Recommendations

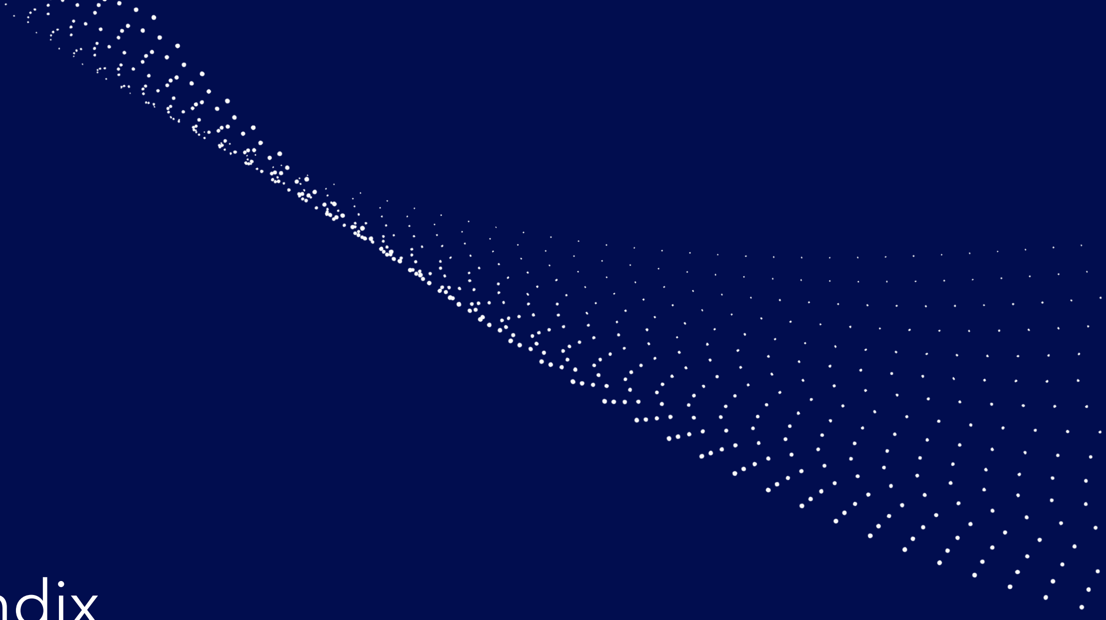
Marine energy technologies offer important benefits when compared to other forms of (renewable) power generation. These benefits may be the primary driver for their large-scale development, which will then also translate into economies of scale and consequent further cost price reductions.

The reviewed technologies provide CO_2-free, predictable, and consistent energy. Salinity plants can in theory supply clean baseload power, operating at least 8,000 full-load hours per year. Tidal and wave energy systems are steadier and more predictable than wind and solar, while also being adjustable and at least partly complementary to them. As such, they can contribute to the diversification of renewable generation and enable a more efficient use of transmission infrastructure if co-located with offshore wind farms.

Therefore, it is important that marine energy technologies are not overlooked by developers, policy makers and parties in search of synergies between options that can help to meet sustainability targets and improve coastal protection. To achieve the Netherlands' bold climate goals, all available resources must be evaluated and utilized. In "Nederland waterland" marine energy may contribute as both bulk generation and balancing of the grid from a societal perspective and help to optimize portfolio revenues for wind farm owners.

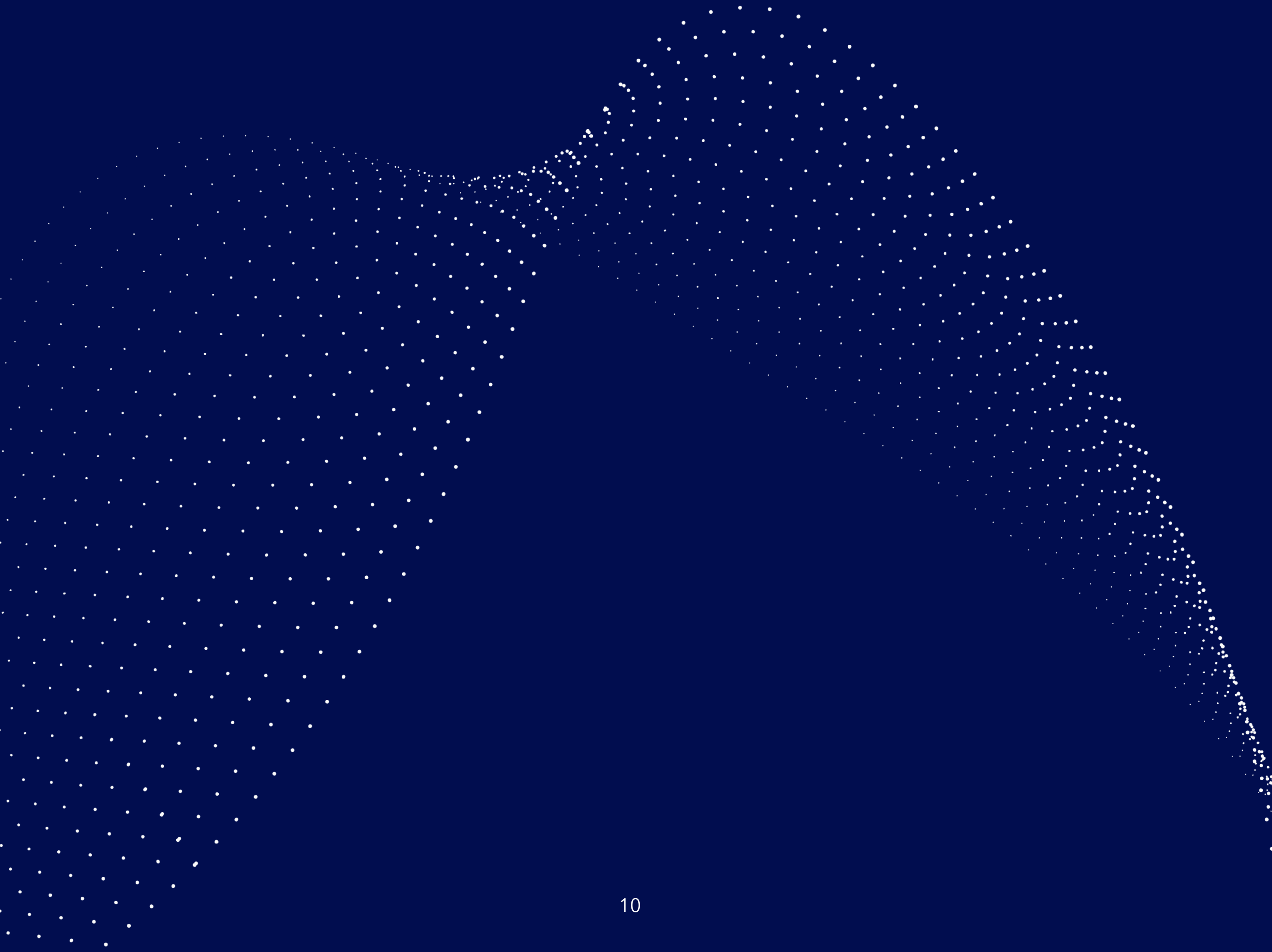
Therefore, the role of marine energy technologies should be clearly defined and integrated within the national renewable policy, considering their potential contribution to the need for multifunctional use of space and infrastructure as stressed in the Draft North Sea Programme 2022-2027 [4].

Further studies, eventually followed by pilot and demonstration projects, are required to investigate and address the uncertainties in marine energy potential and the environmental implications of large-scale marine energy systems. Likewise, including marine energy more explicitly in national subsidy schemes could be a way to support and accelerate its commercial development and to reduce the risk of investments.



Appendix

Brief review of marine energy technologies in the Netherlands



Energy from salinity gradient

OPERATION

Energy from salinity gradient is obtained using membranes between water flows with different salt concentration, usually between fresh and salt water. Riverbeds where the freshwater discharges into the sea are ideal locations for salinity gradient technology. These rivers offer a continuously water flow allowing the salinity gradient plants to potentially run continuously, hence providing CO_2-free baseload power [10].

The most promising technique for generating electricity from salinity gradient in the Netherlands is Reverse Electro Dialysis (RED). Freshwater and saltwater are let through permeable membranes which separate the ions, creating a chemical potential difference. The membranes are arranged in stacks, whose total potential is the sum of the potential difference over all membranes. This total chemical potential creates a voltage and, hence electricity is generated.

POTENTIAL IN THE NETHERLANDS

The technical potential of energy from salinity gradient technologies in the Netherlands is estimated at 6 TWh per year [5]. This is calculated assuming an energy potential of 1.4 MJ per cubic meter of freshwater brought into contact with saltwater, a membrane efficiency of 70%, and 8,000 full-load hours. The main relevant locations for this technology are the mouth of the Nieuwe Waterweg, the Afsluitdijk, and the sea locks in Ijmuiden [5].

Energy from tides

OPERATION

Tidal energy is powered by the natural rise and fall of tides and tidal currents. A large height difference between high and low tide or high to medium current velocities characterize suitable locations for tidal energy technologies.

Compared to other marine energy technologies, tidal technologies are the most matured and advanced, with tidal barrage covering more than 98% of the total marine energy capacity currently operated [11]. The main advantage of tidal technologies is that tides can be predicted well in advance for short and long term, while being independent from weather variations [11]. Depending on the technology, tidal plants can operate on average 2,000 to 2,500 full-load hours [5].

Tidal energy is generated by the following three categories of tidal technologies:

- **Tidal barrage (or tidal range):** Water enters a chamber at high tide, and it is released at low tide, passing through a turbine and thus generating electricity.
- **Tidal stream (or tidal current):** Generally speaking, this technology refers to underwater tidal currents flowing through a device that generates power by moving. Several types of device may be used to harness energy from tidal currents, such as horizontal or vertical axis turbines, oscillating arm with hydrofoil, Archimedes screw, and kites [10].
- **Dynamic tidal power (DTP):** A long T-shape dam is built in the sea, perpendicular to the coast, to influence the tides and create a water level difference on opposite sides of the barrier which feeds turbines, generating electricity.

The TRL of tidal stream technologies varies across the types of devices, with horizontal axis turbines being the most mature with TRL 8, followed by enclosed tips with TRL 7, tidal kite with TRL 6, and vertical axis turbine and oscillating hydrofoil with TRL 5 [12].

POTENTIAL IN THE NETHERLANDS

Tidal barrage technologies are still at a demonstration phase in the Netherlands (TRL 7) [4]. Yet, three locations in Zeeland are suitable, namely Brouwersdam, the Grevelingendam Tidal Technology Center, and Waterduinen. Their total technical potential is estimated up to 45 MW [13], [5]. Assuming 2,400 full-load hours [5], tidal barrage energy could supply up to 108 GWh per year.

As for tidal stream technologies, horizontal axis turbines are applied on a commercial stage (TRL 8) in the Oosterscheldekering by Tocardo [5]. Other technologies are at less mature stage (TRL 5 - 8). Among others, tidal kite technologies have made considerable progress in the Netherlands. A demonstration of the SeaQurrent tidal kite already at the stage of pre-commercial demonstration in an operational environment [14] is planned in Ameland next year. Suitable locations for tidal stream technologies in the Netherlands are the Oosterscheldekering, the drainage shafts of the Afsluitdijk, the Westerschelde, and the Waddenzee [13]. Their total technical potential is estimated up to 100 MW [13], [5]. Assuming 2,500 full-load hours, tidal stream technologies could supply up to 250 GWh per year.

The shallow Dutch coast would be particularly suitable for a Dynamic Tidal Power (DTP) system, which relies on well-known hydraulic concepts and available technologies. Yet, DTP itself is still in the concept phase (TRL 3) [9]. A dam of 30 to 50 km with a capacity of 4 to 15 GW seems technically feasible. Such a dam would supply up to 30 TWh per year, assuming 2,000 full-load hours [5].

Energy from waves

OPERATION

Wave energy converters harvest the energy contained in waves and generate electricity. Wave height, speed, frequency, and water density determine the potential of geographical locations.

There are several pilots and demonstration projects worldwide featuring a variety of devices to harness energy from waves (TRL 5-8). None of them is commercially profitable yet [5]. One of the main challenges that wave energy technologies face is the environmental hostility. Where wave conditions are particularly good, like in oceans, extreme wave conditions may severely damage the devices, hence making wave energy projects more expensive. On the other hand, the Netherlands shows mild wave conditions, which means that the wave energy converters must endure lower forces, making them less expensive [9].

The advantage of wave energy is twofold: it is more reliable than offshore wind and solar, and its energy production profile over time is not synchronized with the energy profile of wind, but rather partly complementary. Wave energy is, therefore, a potential candidate for creating synergies with offshore wind power generation, enabling a more consistent supply of renewable and clean electricity [4].

POTENTIAL IN THE NETHERLANDS

Substantial literature investigates the potential of wave energy in the Netherlands, though it remains uncertain as different applications and concepts are evaluated. The technical potential is often estimated at 1.5 TWh per year. This figure is likely derived from a paper published by Deltares in 2008 [15]. In this paper, Deltares estimated the wave potential along the Dutch coast, assuming that only 50% of Dutch coastal length may be suitable for a line of wave devices. Similarly, Sørensen and Fernández Chozas estimate the theoretic potential at 2.6 TWh, assuming a line of wave devices of 300 km at approximately 30 km from shore [16]. This potential could be raised up to 5.3 TWh per year if a second line of wave energy converters were installed at 80 km from shore. A more recent publication from TKI Wind op Zee, on the other hand, is more skeptical about the feasibility of wave energy, given the rather mild wave conditions and low average wave energy densities along the Dutch coast and in the middle of the North Sea [13].

Nowadays, the marine energy industry itself estimates the technical potential of wave energy at 2.6 TWh when co-located in wind farms (see text box on page 7). This is based on the characteristics of the latest technologies and on the assumption of co-locating wave energy converters within the sea areas already designated for offshore wind turbines.

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