Whitepaper

Offshore wind business feasibility in a flexible and electrified Dutch energy market by 2030

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TNO innovation for life

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Management summary

Offshore wind is the primary supplier of CO2-free electricity moving towards decarbonising the Dutch power system. The installed capacity aims to increase sevenfold to 21.5 GW by 2030. However, the current market trends of increasing renewable capacity, industrial electrification, gas and CO2 prices, the expansion of interconnection, and the need for grid reinforcements are making the power market more volatile. These trends, together with the phasing out of subsidies, result in increasing the risks for offshore wind business.

With this paper, TNO provides insights and recommendations to achieve a profitable offshore wind business under two scenarios by 2030, using TNO's state-of-the-art European power market and dispatching business models. The two scenarios represent the Dutch power system under a low- and high-electrification growth scenario respectively, following current national and European policies for supply and demand. The economic risks for the offshore wind business are investigated.

The recommendations focus on the mitigation of these risks, achieved by developing specific integrated business models between offshore wind developers and industrial flexible assets for power-to-heat (P2H) and power-to-hydrogen (P2H2) conversion.

The low-electrification scenario follows KEV (Klimaat- en Energieverkenning 2021) and the Climate Agreement. There is no explicit target for flexible demand on industrial electrification. On the supply side[1], there is the full deployment of the 21.5 GW of offshore wind.

- The results from this scenario show that the offshore wind business is financially unfeasible by 2030, suffering from the market dynamics of excess supply (even when taking net exports to international markets into consideration). There is a 13% offshore wind curtailment and only 30% of the time in 2030 the electricity price is positive for the business. In this scenario, offshore wind energy has a very low value in the power market.
- A recommendation to achieve a positive business is through direct collaboration between offshore wind producers and industry in the form of specific offshore wind farm connections with flexible assets, such as heat pumps, hybrid boilers, and electrolysers; for example, combining investment and direct electricity exchange via Power Purchase Agreements (PPA). Such agreements could also facilitate the acceleration of industrial electrification from a system perspective.

The high-electrification scenario reflects the impact of potential European policies (RED II and Fit for 55), which provide clear goals on industrial electrification. It has been constructed based on the *Routekaart Elektrificatie (RE)* and the revised version of the Renewable Energy Directive (RED III).

- The results from this scenario show that the renewable capacity is fully utilised. Gas is required when the baseload demand increases and renewable resources are not available, resulting in increased CO2 emissions. There is a high value of offshore wind in the power market. The market price is positive for the offshore wind business in 80% of the cases.
- The offshore wind business is feasible in the power market. PPAs are still recommended to create an integrated business model that can benefit both the industrial end users of offshore wind and help the energy system reach its decarbonisation objectives and reduce CO2 emissions. They can also support the hedging of fluctuating electricity prices and thus reduce the volatility of the power market.

1 This study assumes that by 2030 gas prices are stabilised at a low level (duration curve from €20/MWh up to more than €100/MWh) after the current gas crisis, assuming LNG-driven based on the longer market projections following the World Energy Outlook

1 Introduction

1.1 Market challenges for offshore wind by 2030

Offshore wind energy is the cornerstone in the rollout of renewable electricity for a climate-neutral Europe by 2050, with the interim target of a reduction of greenhouse gas emissions of 55% (compared to 1990) by 2030 [1]. The Netherlands is one of the most ambitious countries in Europe: 2022's latest and more stringent targets will result in a renewable energy portfolio increase and an additional reduction obligation of approximately 15 Mt of CO_2 in different sectors, following, amongst other things, from the increased use of green hydrogen and energy savings. Offshore wind is forecasted to be the primary contributor to a CO_2-free Dutch power system. Its production aims to increase sevenfold from 3 GW in early 2022 to 21.5 GW by 2030 [2] [3], supplying between 45% and 58% of the total electricity estimated demand (Figure 1a).

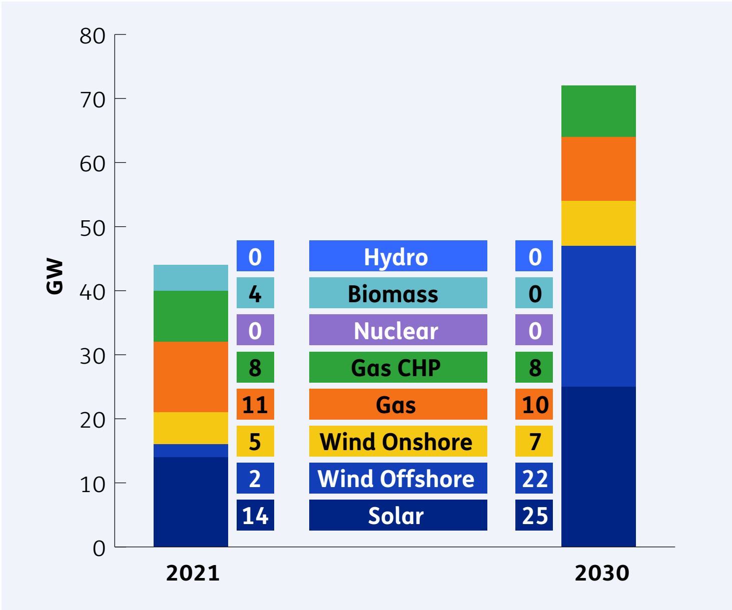


Figure 1a. Power generation capacities in the Netherlands in 2021 and expectations for 2030.

On the supply side, in a decarbonised power sector with a high share of renewable power generation, price volatility is much more important than today. The same applies to the associated cannibalisation effect, whereby offshore wind undermines its own business case as its supply increases. This constitutes a financial risk for offshore wind investments, but also for other production or storage technologies, making the profitability of the offshore wind business less certain.

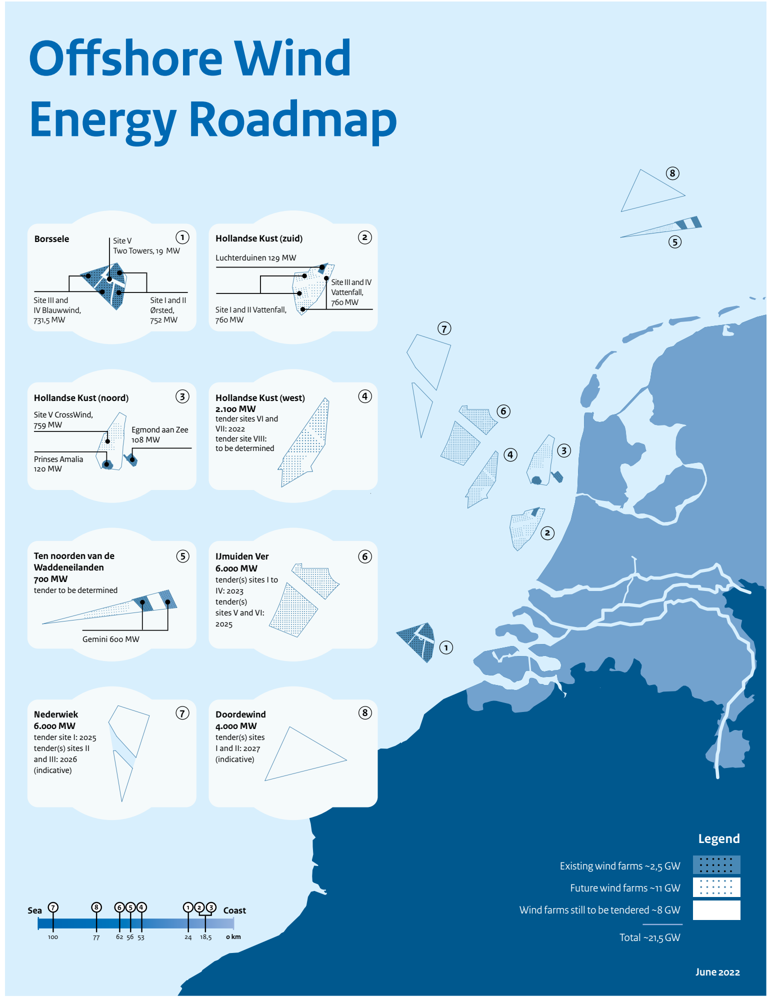


Figure 1b. New areas opened by the Dutch government to accommodate for the revised ambitions and newer targets of the 21.5 GW offshore wind portfolio by 2030.

On the demand side, the key challenge is to safeguard the optimal match between flexible electricity demands and the supply of renewable energy, which is envisioned to mainly consist of offshore wind. At the same time, the country's large industrial sector requires a large volume of alternatives to fossil-based feedstock and heat to supply demand, making industrial electrification[2] a key driver of the transition and an important pillar for the offshore wind business. As a power supplier, the uncertainties associated with the electrification growth in the coming years, the possible migration of production to lower-cost countries, and uncertainties surrounding the role of hydrogen imports within Europe and via intercontinental trade routes make the fluctuating demand another market challenge for wind investments.

1.2 Goal of the study

TNO provides insights and recommendations for developing a long- lasting offshore wind business under two policy-driven energy scenarios (high- and low-electrification growth) by 2030:

- The **low-electrification scenario** follows KEV *(Klimaat - en Energie-verkenning 2021)* and Climate Agreement policies by 2030. There is no explicit target for flexible demand on industrial electrification. On the supply side[3], there is the full deployment of 21.5 GW offshore wind capacity.
- The **high-electrification scenario** reflects the impact of potential European policies resulting from REDII and Fit for 55, which suggest clear goals on industrial electrification. It is founded on the Routekaart Elektrificatie (RE), which considers electrification in industry, and has been updated with the new plans of Tata Steel to reduce emissions via electrification, and the revised third version of the Renewable Energy Directive (RED III), which features an obligation to use renewable fuels of non-biological origin (RFNBOs). For the transport sector, a (single-counted) target of 2.6% RFNBOs use is introduced, and a new target for a 50% share of renewables in hydrogen consumption in the industry (which includes non-energy uses) is considered.

The increase in electrification from the low- to the high-electrification scenario results from higher sector-specific target emission reductions. In industry, power-to-heat (P2H) offers major flexibility potential, since it can be covered by hybrid boilers, which can alternate between gas and electricity depending on commodity prices. On the supply side, the aim is to capture the 21.5 GW of wind offshore generation together with the 2022 targets for other renewable energy sources and the domestic electricity supply from (cross-border) electricity imports by 2030 (Figure 2).

2 https://www.topsectorenergie.nl/nieuws/routekaart-elektrificatie-laat-de-grote-potentie-van-elektriciteit-voor-de-industrie-zien
3 This study assumes that by 2030 gas prices are stabilised at a low level (duration curve from €20/MWh up to more than €100/MWh) after the current gas crisis, assuming LNG-driven based on the longer market projections following the World Energy Outlook.

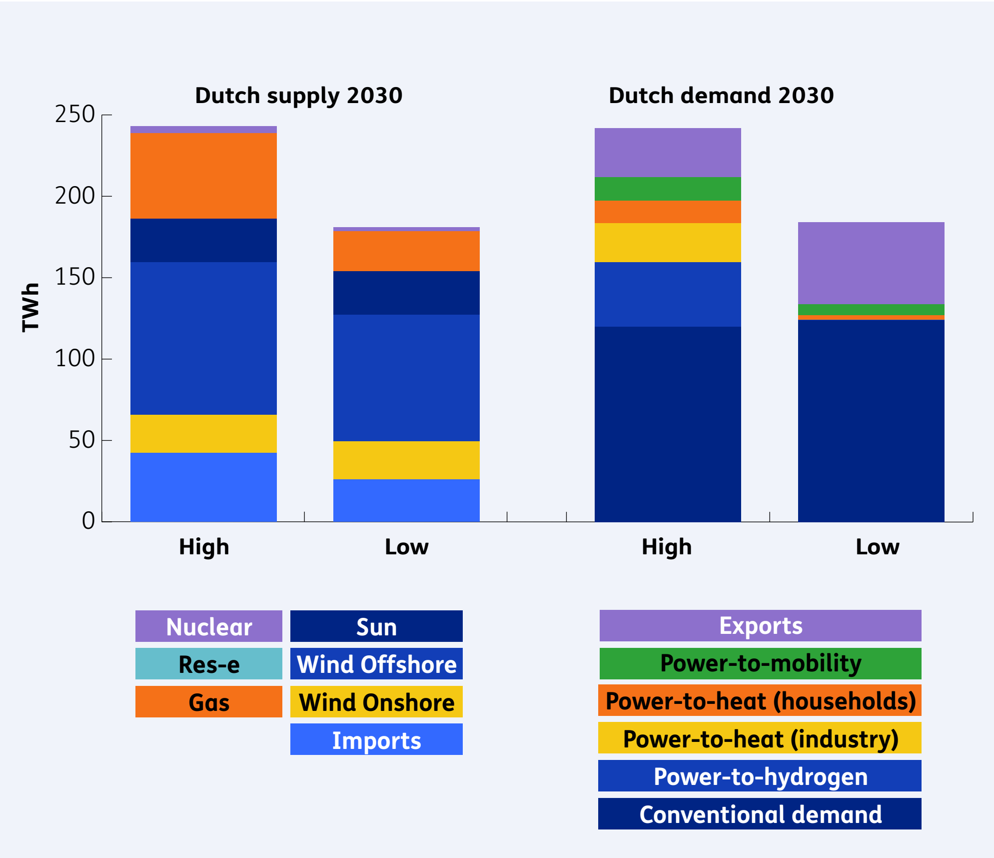


Figure 2. The Netherlands' high- and low-electrification scenarios for electricity demand and supply in 2030.

This study presents the conditions under which offshore wind can be profitable in a changing energy market, both from a flexible (electricity) demand side and from the supply side (increasing renewable capacity), answering the following questions:

- Matching supply and flexible demand in a system that is being electrified, how is the Dutch energy market affected by industrial electrification and what is the situation for the offshore wind business case?
- Considering the technology cost reduction and the zero-subsidy financial mechanism, what are the risks involved with a spot price and its mitigation? How can we realise a long-lasting offshore wind business case with a new market approach?
- Regarding offshore wind in collaboration with electrified industry, what is the value of an integrated business model between offshore wind and electrified industry via a virtual PPA?

The structure of this report is as follows. Chapter 2 describes the holistic modelling approach and the tools applied in this study using power market models and business models.

Chapter 3 shows the results obtained for the study. These results have been split: the first results (3.1) are based on the situation of the Dutch energy market by 2030, driven by industrial electrification and the impact on the offshore wind sector as a whole; the second results (3.2) show the offshore wind business profitability and the new market approach suggested to achieve a positive, long-lasting offshore wind business case.

Chapter 4 features the main conclusions of the study.

2 Modelling approach

The scenarios represent the Dutch electricity system calculated with European power system model COMPETES (COMPetition in Electric Transmission and Energy Simulator), a power system optimisation and optimal dispatch model that seeks to minimise the total power system costs of the European power market, while accounting for the technical constraints of the generation units and transmission constraints between countries.

A power dispatching tool (EYE model) is then employed to set a range of sensitivities and identify the options for a positive offshore wind farm, using the COMPETES simulations and scenarios as input. As a power market simulator, the EYE model assesses the effects on energy prices in the market one day ahead, based on different sources of supply, expected demand, marginal costs, and prices defined by the individual assets that make up an intended power system.

Within a power system, each asset can be defined based on its technology, efficiencies, marginal costs, fuel sources, or generation profiles.

The offshore wind business case is analysed using the EYE results (prices and volumes). Collaboration between industry and offshore developers is analysed through contracts of PPA modelling. A PPA is simulated using an integrated business case in which there is an exchange of energy between offshore wind and a flexible asset. The combination of the business case of offshore wind and the flexible asset reveals whether a PPA can be beneficial.

There are several types of PPA that target different goals and boundary conditions of the integrated business model. In this study, the virtual PPA[4] model is analysed, which is a flexible PPA without must-run clauses.

The choice to analyse this type of PPA was made because it directly shows the impact of an integrated business model in terms of economic results. In practical situations, other goals and boundary conditions will lead to different PPA constructs.

The virtual PPA is modelled as part of an integrated business case of the offshore wind asset and a flexible asset (electrolyser or power-to-heat). Both assets bid on the electricity market, after which the PPA is calculated. Every hour, the maximum amount of electricity is flowing from the offshore wind to the flexible asset. An excess supply of wind is then sold on the market. If the flexible asset has a remaining demand, then this is bought on the market. The integrated business case considers the cost of the remaining demand and the benefits of the remaining supply of offshore wind and the supply of the product (hydrogen or heat).

It is important to note that, in reality, offshore wind and the flexible asset will need to negotiate a PPA price. This price has a large effect on the individual business cases.

However, it does not influence the integrated business case, in which the offshore wind and flexible asset is considered to be one single compound asset.

4 In the virtual PPA model, the power producer sells the generated electricity in the wholesale power market. The payments received by the power producer from the fluctuating wholesale power price are net settled against the PPA price agreed with the corporate buyer. The corporate buyer continues to purchase electricity for its facilities under its local contracts. As the virtual PPA contract is a financial settlement, a physical network connection between the generation asset(s) and the load is not necessary.

3 Results and discussions

3.1 Dutch energy market by 2030 driven by industrial electrification

This section shows the first results of the study for the Dutch energy market by 2030, driven by industrial electrification and the impact on the offshore wind sector.

On the supply side, the Dutch power system is experiencing an evolution marked by the introduction of new technologies, such as variable renewable energy (wind and solar) and storage technologies. On the demand side, there is an expected increase, due to the electrification of sectors in which energy is currently mainly derived from fossil fuels. These sectors include mobility, the built environment, and industrial processes.

This electrification is based on power-to-heat (P2H) technologies (such as industrial heat pumps or hybrid boilers that can alternate between running on electricity and natural gas), or indirectly, on power-to-hydrogen (P2H2) technologies that use CO2-free electricity to produce hydrogen as a feedstock or energy carrier for industry. The Sankey diagrams in Figure 3 show the distribution of the sources between the supply and (non-flexible and flexible) demand for electricity for both scenarios. Note that the net imports and exports of both scenarios have been absorbed in the static electricity demand of the model. The impact of increasing the electricity demand results on imports and exports, the gas fuel generation variability and the increase in CO2 prices.

Imports/Exports: The high-electrification scenario shows a net import position of 14 TWh. Conversely, in the low-electrification scenario, the Netherlands becomes a net exporter (23 TWh). The change from exporter to importer is due to the extra electrification on the system, meaning that the national demand can be (partly) met with curtailed wind energy. Nevertheless, the increase in electricity demand is almost 80 TWh, requiring extra imports and an increase in the output of the gas-fired powerplants to balance the system. Note that the changing goals of other countries close to the Netherlands may alter the results of the imports and exports. Some countries may increase their goals for renewable electricity in the period leading up to 2035. This will also have an amplifying effect on the market dynamics in the Netherlands.

Increase in gas-fuelled generation:
The increase of gas-fired generation (almost 30 TWh) in the high-electrification scenario is due to a shortage of variable renewable energy during hours in which the baseload demand increases. Offshore wind covers significant parts of both inflexible and flexible demand. Nevertheless, offshore wind cannot cover the whole demand when there is low wind resource, meaning gas is required to offer more flexibility. Power-to-heat (P2H) technologies require gas-fired electricity driven by the hydrogen demand assumptions. Therefore, in a system with only electrification (including the use of hydrogen), a potential lack or underestimation of variable renewable sources would, under normal market conditions, mean that aligning supply and demand would require power generated by gas-fired units, resulting in an increase in greenhouse gas emissions. More investigation into the further demand of hydrogen would be necessary to reduce CO2 emissions and the use of gas-fired powerplants.

Increase in CO2 emissions: The increase in generation of the gas-fired powerplants, to provide electricity for the baseload demand when renewable power sources are lacking, results in an increase of CO2 emissions in the high-electrification scenario of 10 Mt when compared to the low-electrification scenario. This represents an increase of 120% of emissions related to the power system. This result aligns with the need for more renewable energy to keep emissions low.

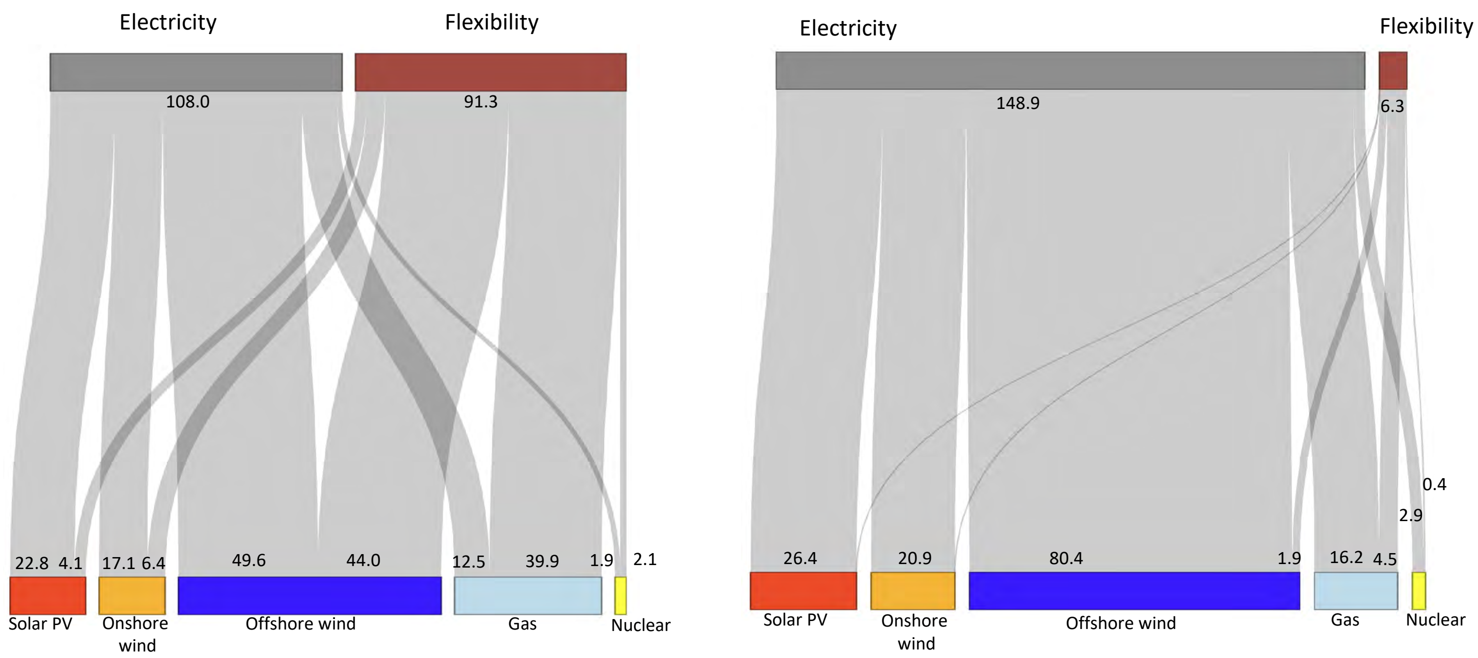


Figure 3. Contribution of supply sources towards meeting electricity and flexible demand in the (left) high- and (right) low-electrification scenarios for the Netherlands (all numbers are in TWh).

From a system perspective, on the one hand, offshore wind targets are set to 21.5 GW by 2030. However, the supply capacity should be flexible if electrification is lower than estimated to match supply and demand.

On the other hand, more support on the demand side is needed for higher direct electrification, such as P2H, or indirectly, by means of P2H2. From a system perspective, an optimal social approach would be to optimise the most appropriate renewable generation mix to meet a set demand.

3.2 New market approach for a long-lasting offshore wind business

A wind farm of 2 GW of the 21.5 GW of the offshore wind portfolio by 2030 is considered to study the offshore wind business case under the two scenarios of high and low electrification. The wind farm is considered price-taker technology, and thus not influencing market prices and behaviour. Current trends in the increasing size of offshore wind turbines are expected to continue. (By 2030, turbines could reach power ratings of 20 MW.) Layout optimisations and farm control strategies might see offshore wind farms with capacity factors of up to 55% and the levelised cost of energy of around €40/MWh [4].

This study focuses on the value of Power Purchase Agreements (PPAs) in hedging price fluctuations both for off-takers and offshore wind developers, following the uncertainties of the power system by 2030. The following integrated business models have been analysed to address such a PPA construct:

- Market: The business model consists of an investment in the 2 GW offshore wind farms. The produced electricity is fed into the grid and sold in the electricity market.
- PPA heat: The integrated business model comprises an investment in the offshore wind farm and a 2 GW electric boiler. There is a PPA between the offshore wind farm and the electric boiler.
- PPA hydrogen: The integrated business model comprises an investment in the offshore wind farm and a 2 GW electrolyser. There is a PPA between the offshore wind farm and the electrolyser.

There are several drivers behind constructing a PPA, based on [5]:

- Offshore wind developers and consumers creating a strong pipeline of projects to secure a route-to-market.
- Governments can reduce support schemes when renewables can compete with market prices.
- Offshore wind developers reduce the risk of exposure to longer-term price fluctuations.
- Off-takers achieve recognition for using renewable energy and unlock value when PPAs beat market prices.

In this section, insights into risks involved with spot price exposures in the high- and low-electrification scenario are presented. This is followed by an analysis of the impact of PPAs on the integrated business model of offshore wind with industrial parties (Figure 4). Lastly, the impact of these integrated business models on the industrial assets is qualitatively assessed.

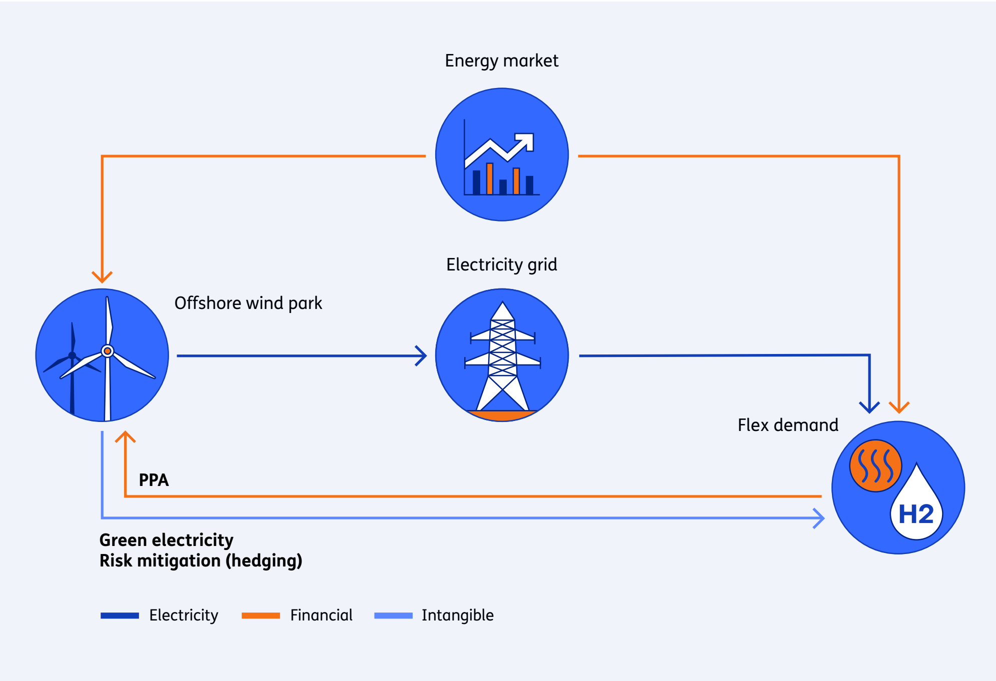


Figure 4. Value network of the integrated business model, including a PPA. The financial value shared with the offshore wind park is met by intangible values (green electricity, price hedging).

Modelling of the integrated business case
The virtual PPA is modelled as part of an integrated business case of the offshore wind asset and a flexible asset (electrolyser or power-to-heat). Both assets bid on the electricity market, after which the PPA is calculated. Every hour, the maximum amount of electricity is flowing from the offshore wind to the flexible asset. An excess supply of wind is then sold on the market. If the flexible asset has a remaining demand, then this is bought on the market.

The integrated business case considers the cost of the remaining demand and the benefits of the remaining supply of offshore wind and the supply of the product (hydrogen or heat).

It is important to note that, in reality, offshore wind and the flexible asset will need to negotiate a PPA price. This price has a large effect on the individual business cases.

However, it does not influence the integrated business case, in which the offshore wind and flexible asset is considered one single compound asset.

In the high-electrification scenario, there is 100% utilisation of the offshore wind production towards meeting demand, while in the low-electrification scenario, there is significant curtailment (13%). Even when considering the declining costs of offshore wind technology towards the levelised cost of energy (LCoE) of approximately €40/MWh [4], the zero-subsidy tender, and the cannibalisation effect render the business case for offshore wind unprofitable in the low-electrification scenario (if the business case only relies on the spot market). Looking at a year, it is estimated that prices are >€40/MWh 30% of the time. On the contrary, for the high-electrification scenario, prices are >€40/MWh 80% of the time, making the offshore wind business case positive and more stable.

The value of offshore wind in the spot market[5] is higher in the high- (€49.7/MWh) than in the low-electrification scenario (€32.8/MWh) (Table 1) due to the presence of more (flexible) demand assets. In the high-electrification scenario, demand levels are typically higher, more often rendering supply from expensive natural gas assets as the marginal technology. Visualising the offshore wind participation along with the price duration curve, there is a decrease in offshore wind contribution with increasing clearing prices (Figure 5).

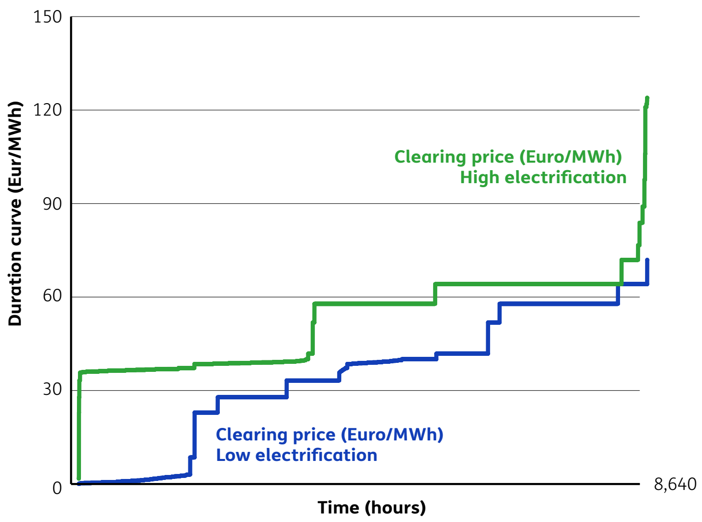
This is expected, as during timesteps of high offshore wind production, the demand is mainly supplied by wind, which has low marginal costs, therefore resulting in low average clearing prices. However, when offshore wind production is low, mainly due to low resource availability, the demand is supplied by gas-fired assets, creating high average clearing prices due to their higher marginal cost.

Statistics for prices (€/MWh)	High electrification	Low electrification
Average clearing price	53.7	34.7
Value of the wind	49.7	32.8
Max. clearing price	300 (max. capacity)	73
Min. clearing price	2.8	1.1
Peak clearing price (97% percentile)	73.0	65.2
Off-peak clearing price (3% percentile)	37.2	1.5
Average peak clearing price	81.3	65.3
Average off-peak clearing price	36.4	1.4
Number of peak hours (-)	445	398
Number of off-peak hours (-)	314	314

Table 1. Clearing price statistics for high- and low-electrification scenarios.

5 This study assumes that by 2030 gas prices are stabilised at a low level (duration curve from €20/MWh up to more than €100/MWh) after the current gas crisis, assuming LNG-driven based on the longer market projections following the World Energy Outlook.

Figure 5(a) shows the clearing price duration curve in the high- and low-electrification scenarios. The largest differences in prices for the two curves occur at the extremes (up to 1,500 hours and after 8,000 hours). In the low-electrification scenario (up to 1,500 hours), the low prices are set by renewable sources. In the high-electrification scenario (after 8,000 hours), the high prices are set by expensive gas assets, increasing prices significantly. Figure 5 (bottom) shows scatter plots when comparing the offshore wind production by 2030 in the two scenarios. The highest density of data points is seen on the diagonal line, indicating that offshore wind utilisation is identical in the high- and low-electrification scenarios. The region of points below the diagonal line shows the curtailment of wind in the low-electrification scenario. Wind production in the low-electrification scenario is lower than in the high-electrification scenario.



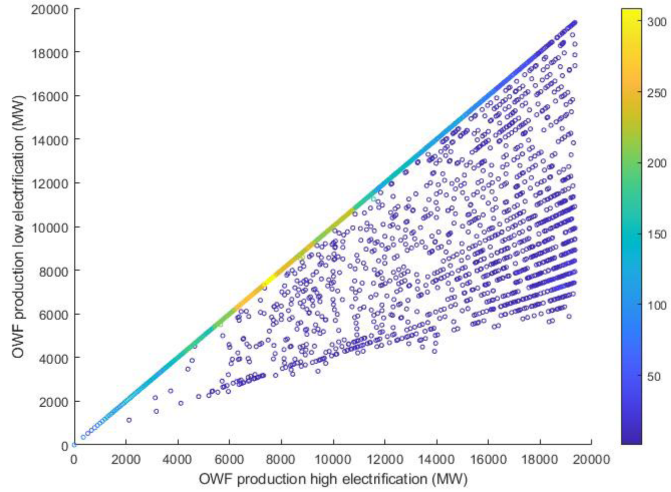


Figure 5. Top: clearing price[6] duration curve for the high-electrification scenario (orange) and low-electrification scenario (yellow). Bottom: scatter plot showing offshore wind production in the high- and low-electrification scenarios (including curtailment) for the full OWF portfolio. Colour bar indicates the frequency of the occurrence (h) of the offshore wind power production.

6 This study assumes that by 2030 gas prices are stabilised at a low level (duration curve from €20/MWh up to more than €100/MWh) after the current gas crisis, assuming LNG-driven based on the longer market projections following the World Energy Outlook.

The analysis of the business case is performed for different prices for CO2 and H2 under the low- and high-electrification scenarios. For each situation, the integrated business model with the best economic results is determined using a market-based model. An investment in the offshore wind farms is conducted. Produced electricity is sold to the electricity market or, via a Power Purchase Agreement (PPA), to a flexible asset.

A sensitivity analysis of the market business case of offshore wind shows that the business case of offshore wind:

- Is positively impacted by increased electrification, which makes the business case positive under the assumptions of this analysis. The Internal Rate of Return (IRR) ranges from 4-14% in the high-electrification scenario and between -3% and 4% in the low-electrification scenario.
- Is positively impacted by higher CO2 and H2 prices, which can make the business case positive, even in the low baseload electrification scenario. At a CO2 price of €150/tonne, the IRR increases to 4%, creating a feasible business case.

The offshore wind supplies to various types of demand (electricity and flexible demand) and the conditions leading to curtailments are presented for the two scenarios (high and low electrification) (Table 3 and 4). In the high-electrification scenario, flexible assets operate at a minimum load condition, increasing the flexible demand to the desired electrification targets of the given scenario technologies. The main demand source in the low-electrification scenario, however, is a result of conventional electrical demand and net exports (listed together as electricity demand in Table 2).

In the high-electrification scenario, the full offshore wind portfolio contributes 54% to the electricity demand and 46% to the flexible demand. The 2 GW virtual wind farm under the high-electrification scenario supplies less towards electricity demand (39%) than flexible demand (61%) (Table 3) due to a higher a bidding price. This indicates that wind farms could supply green power to industry and green fuel production through flexible assets, such as heat pumps, hybrid boilers, and electrolysers, thus directly participating in the electricity market. Overall, the results under this scenario are in favour of a positive offshore wind farm business with the electricity market because it is 100% utilised in a high-electrification system, with curtailment being practically non-existent (0%) (Table 4).

As a result of very low flexible demand, in the low-electrification scenario, the offshore wind contribution is almost exclusively used to meet baseload electricity demand (99%), with around 12-13% curtailment in all sensitivities (Table 3 and Table 4). It indicates that, both from a system perspective and from a business case perspective, there is still room for higher system electrification, and thus, higher flexible demand. The curtailed wind power may be used to supply green power directly to industry and increase electrification through PPAs.

High electrification					
Order of strategies		H2 Price (€/kg)			
		€2	€3	€4	€6
CO2 price (€/tonne)	€50	4%	5%	6%	9%
	€100	7%	8%	9%	11%
	€150	10%	11%	12%	14%

Low electrification					
Order of strategies		H2 Price (€/kg)			
		€2	€3	€4	€6
CO2 price (€/tonne)	€50	-3%	-3%	-3%	-3%
	€100	1%	1%	1%	1%
	€150	4%	4%	4%	4%

Figure 6. IRR of the market-based offshore wind business model.

Offshore wind contribution (TWh, %)	High electrification	Low electrification
Offshore wind to electricity demand	46.2 (54%)	74.3 (99%)
Offshore wind to flexible demand	38.6 (46%)	0.5 (1%)
Virtual wind farm to electricity demand	3.4 (39%)	6.1 (80%)
Virtual wind farm to flexible demand	5.3 (61%)	1.4 (18%)

Table 2. Offshore wind contribution to electricity and flexible demand per scenario.

	High electrification	Low electrification
Curtailment OWF (TWh)	0.01	10.10
Curtailment OWF (%)	0%	12%
Curtailment OWF (virtual) (TWh)	0.0	1.10
Curtailment OWF (virtual) (%)	0%	13%

Table 3. Offshore wind farm curtailment in high- and low-electrification scenario.

The virtual PPA model is analysed through the impact on the clearing volumes of the power market model [6]:

‘In the virtual PPA model, the power producer sells the generated electricity in the wholesale power market. The payments received by the power producer from the fluctuating wholesale power price are net settled against the PPA price agreed with the corporate buyer. The corporate buyer continues to purchase electricity for its facilities under its local contracts. As the virtual PPA contract is a financial settlement, a physical network connection between the generation asset(s) and the load is not necessary.’

In the low-electrification scenario, 2 GW of electric boiler or electrolyser capacity is added to the system due to the PPA, as we concluded from the system analysis that this scenario leaves room for additional electrification. In this scenario, it is assumed that policy does not ensure this flexible demand, even if the potential is there. A PPA between an offshore wind asset and industry will lead to extra capacity. In the high-electrification scenario, 2 GW of existing electric boiler or electrolyser capacity is used for a PPA. In this scenario, policy ensures a high level of electrification and a PPA will be made with the existing capacity, instead of additional capacity. The PPA construct has no effect on the operation of the system. Both the offshore wind asset and the flexible demand will bid as if there is no PPA. The PPA is a financial settlement between the two assets, set up outside of the electricity market. Consequently, the operation and business cases of other assets bidding on the market are not influenced by the PPA.

High electrification					
Order of strategies		H2 Price (€/kg)			
		€2	€3	€4	€6
CO2 price (€/tonne)	€50	4%	5%	10%	22%
	€100	7%	8%	9%	20%
	€150	10%	11%	12%	18%

Low electrification					
Order of strategies		H2 Price (€/kg)			
		€2	€3	€4	€6
CO2 price (€/tonne)	€50	3%	6%	14%	30%
	€100	6%	6%	11%	27%
	€150	9%	9%	10%	24%

Legend		
Market	PPA Heat	PPA H2

Figure 7. IRR of the best-performing integrated business model, with the associated business model.

The analysis of the business case follows a simple business model, omitting infrastructure costs, and using market prices from the EYE model, which are subject to several uncertainty factors. Therefore, the results should be interpreted as trends and not as an investment analysis.

The analysis of the PPA business models show that **in the low-electrification scenario, a PPA with heat or hydrogen improves the IRR by 5-33%**, compared to the market-based model. Furthermore, **in the high-electrification scenario, the PPA business model can also improve the business case of a feasible offshore wind farm, when hydrogen prices are higher than €4/kg**. The IRR of offshore wind ranges from 4-14%, and can improve up to 22% for the integrated business model with a PPA. **The energy carrier for which a PPA (heat or hydrogen) has the best economic value is determined by CO2 and hydrogen prices**, as shown in Figure 7.

In this analysis, the virtual PPA construct to make an offshore wind farm economically feasible reduces the average revenue of the flexible asset, thus reducing the IRR of these assets. The asset owners, mostly industry parties, can seek other routes to maintain an economic case to participate in the integrated business model. For instance, the asset owner can gain value by achieving recognition for using renewable energy and reaching decarbonisation objectives, or by hedging potential fluctuating electricity prices.

Analysis of the dynamics on the electricity market shows that an increase in offshore wind is beneficial for the average electricity price of flexible assets. Developing integrated business models will therefore also have a hedging value for these actors. The PPA construct can yield an economic risk or green premium (through green certificates) for the flexible asset owner.

Current developments in the implementation of the Renewable Energy Directive II (RED II) suggest that renewable hydrogen producers will be allowed to procure electricity from the grid (if it comes from renewable energy sources), which can be secured by signing PPAs with variable renewable energy producers. This will help reach decarbonisation objectives and hedge potential fluctuating electricity prices. An increase in offshore wind is beneficial for the average electricity price of flexible assets. Developing integrated business models will therefore also have a hedging value for these actors.

4 Conclusions

Offshore wind is the primary supplier of CO2-free electricity by 2030, moving towards decarbonising the Dutch power system. The installed capacity aims to increase sevenfold to 21.5 GW by 2030.

However, the current market trends of increasing renewable capacity, industrial electrification, gas and CO2 prices, and the need for grid reinforcements are making the power market more volatile. These trends, together with the phasing out of subsidies, are increasing the risks for offshore wind business.

TNO provides insights and recommendations for developing a long- lasting offshore wind business under two (high- and low-electrification) policy-driven energy scenarios by 2030.

THE LOW-ELECTRIFICATION SCENARIO follows the current targets on the supply side for renewable energy set by the government by 2030. **The flexibility to match supply and demand is given to the system via the supply side in the form of 13% wind curtailment. Offshore wind suffers from the market dynamics of excess supply, even when taking net exports into consideration.** The IRR of the offshore wind farm is between -3% and 4%, after taking sensitivity to the hydrogen and CO2 prices into account. A positive business case only occurs when CO2 prices exceed €150/kg. **This means that the offshore wind sector needs to look for other types of business models. This can be achieved by cooperating with industry in integrated business models via combined investment and direct electricity exchanges through Power Purchase Agreements (PPA).** These PPA contracts can increase the IRR of the integrated business model by 5-33% when compared to a single offshore wind powerplant, thus reverting it to a positive business case. The electrolyser is the best asset through which to form a PPA at a hydrogen price of €4/kg or higher. For lower hydrogen prices, the electric boiler performs better economically.

THE HIGH-ELECTRIFICATION SCENARIO reflects the impact of potential European policies following RED II and Fit for 55, which lay out clear goals for industrial electrification. The increase of gas generation of almost 30 TWh in the high-electrification scenario is due to a shortage of variable renewable energy during hours in which the baseload demand increases. **Offshore wind covers a significant part of the electricity demand. Nevertheless, offshore wind cannot cover the whole demand, making gas a requirement to offer more flexibility.** Power-to-heat (P2H) technologies require gas-fired electricity, driven by the hydrogen demand assumptions. Investigation of the further demand of hydrogen would be necessary to reduce CO2 emissions and the use of gas-fired powerplants. A large number of flexible assets are considered (from electrolysis and heat technologies) to full utilise the 21.5 GW of offshore wind. **The wind has a high value; by 2030, it is profitable in the power market 80% of the time. A PPA construct with an electrolyser could improve the business case even further** when the hydrogen price is €6/kg (or at €4 /kg with a CO2 price of €50/tonne). At a hydrogen price of €2/kg and a CO2 price of €150/tonne, the hybrid boiler is the best-performing option. The IRR of the market-based offshore wind model ranges from 4%-14% and can improve up to 22% for the best integrated business model with a PPA.

The direct integration of offshore wind with flexible assets for power-to-heat (P2H) and power-to-hydrogen (P2H2) conversion by means of a PPA improves the offshore wind business.

Furthermore, this integration can support the hedging of fluctuating electricity prices and thus reduce the volatility of the power market. **The integrated business model can benefit both the industrial end users of offshore wind and help the power system reach decarbonisation objectives.**

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To have a network for sustainable (wind) energy in the future, we all need to make a big deal today. Because climate change starts with system change. That is why TNO is working today with partners on tangible system solutions to bring offshore energy efficiently to land. Smartly matching supply and demand. But also, on biodiversity around wind farms. We can only achieve the climate goals if we work on tomorrow's system today.

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