Report

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

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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 CO2 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 CO2-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).

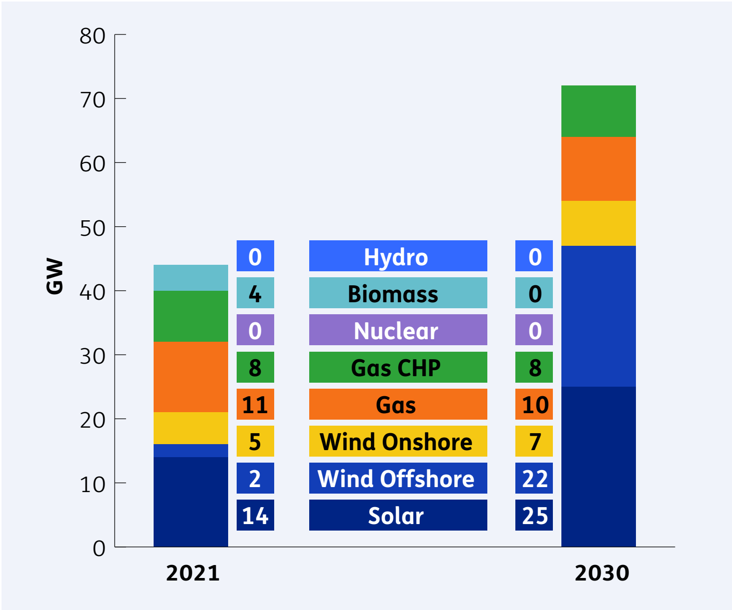

Figure 1a. Power generation capacities in the Netherlands in 2021 and expectations for 2030.

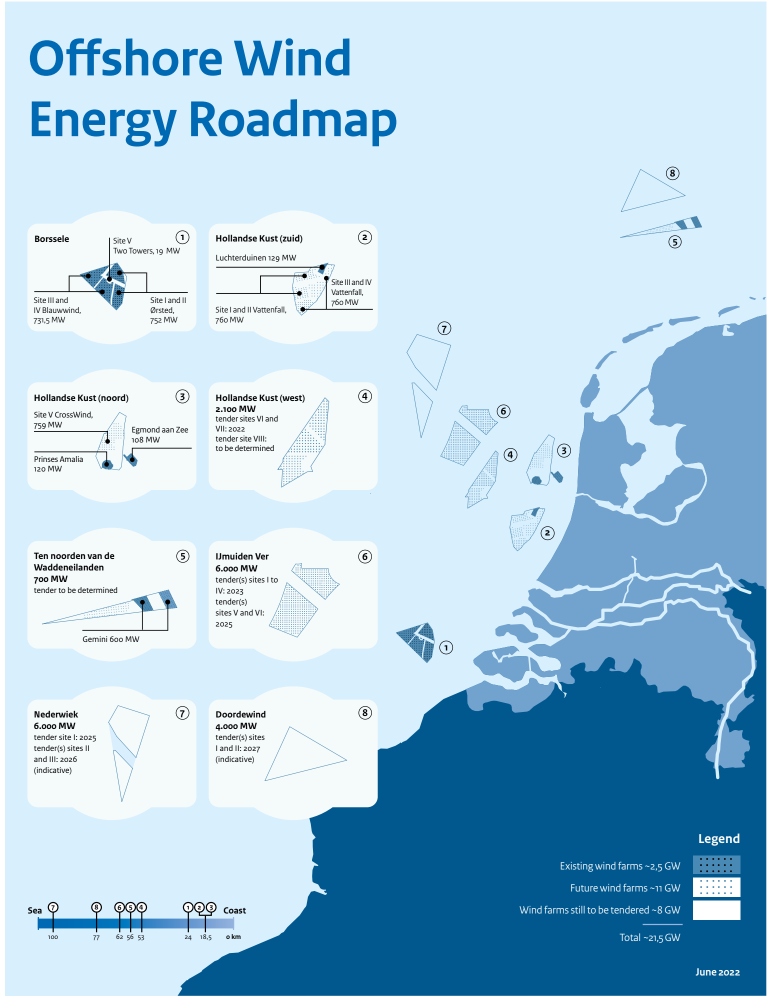

Figure 1b. New areas opened by the Dutch government to accommodate for the revised ambitions and newer targets of the 21.5 GW offshore wind portfolio by 2030.

On the 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.

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.

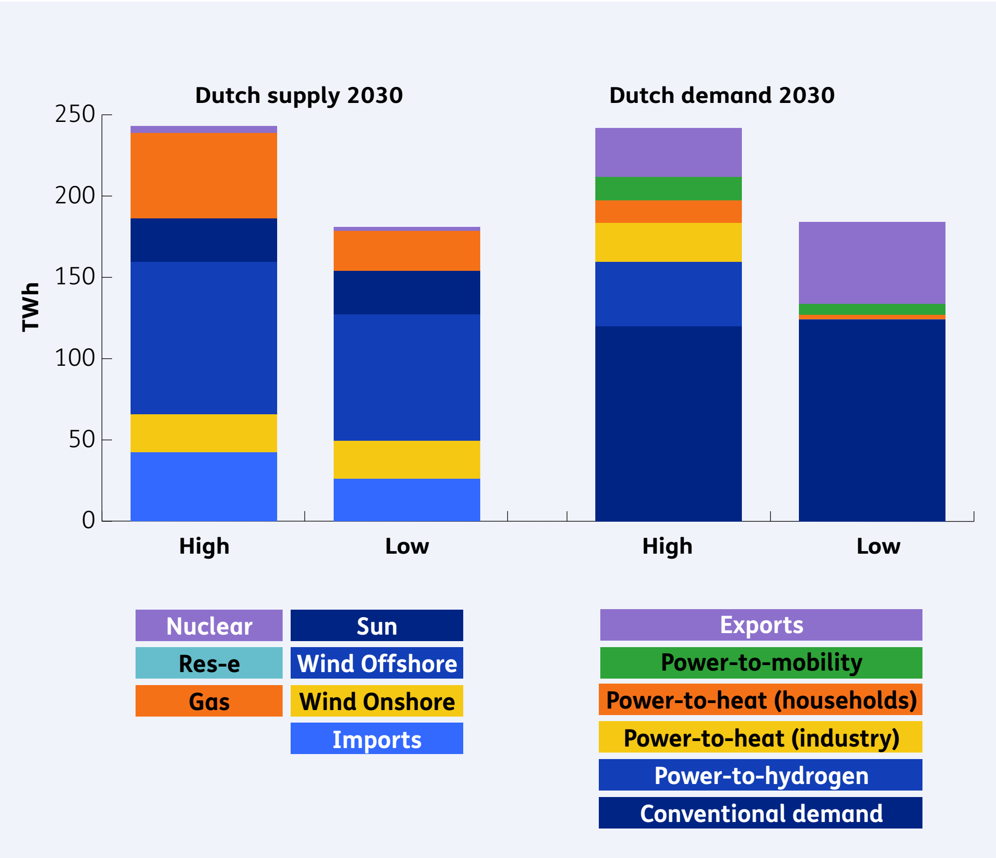

Figure 2. The Netherlands' high- and low-electrification scenarios for electricity demand and supply in 2030.

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.

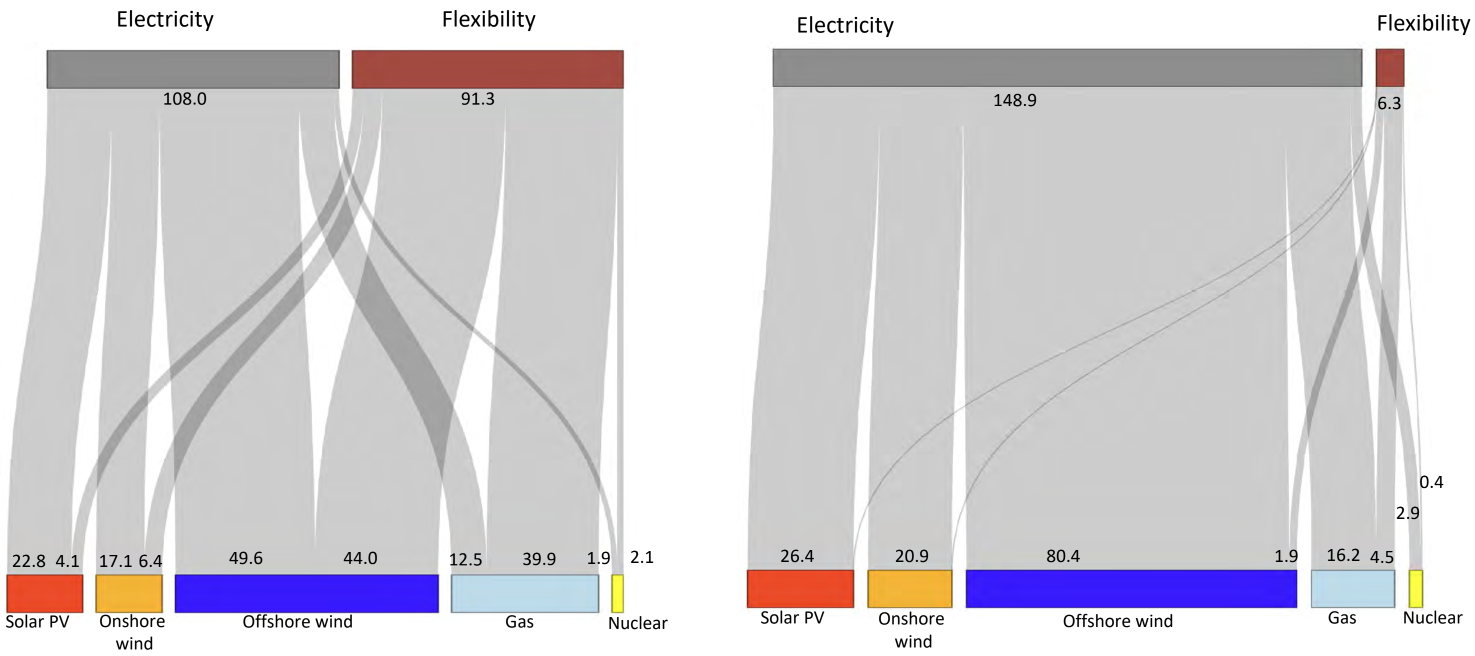

Figure 3. Contribution of supply sources towards meeting electricity and flexible demand in the (left) high- and (right) low-electrification scenarios for the Netherlands (all numbers are in TWh).

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.

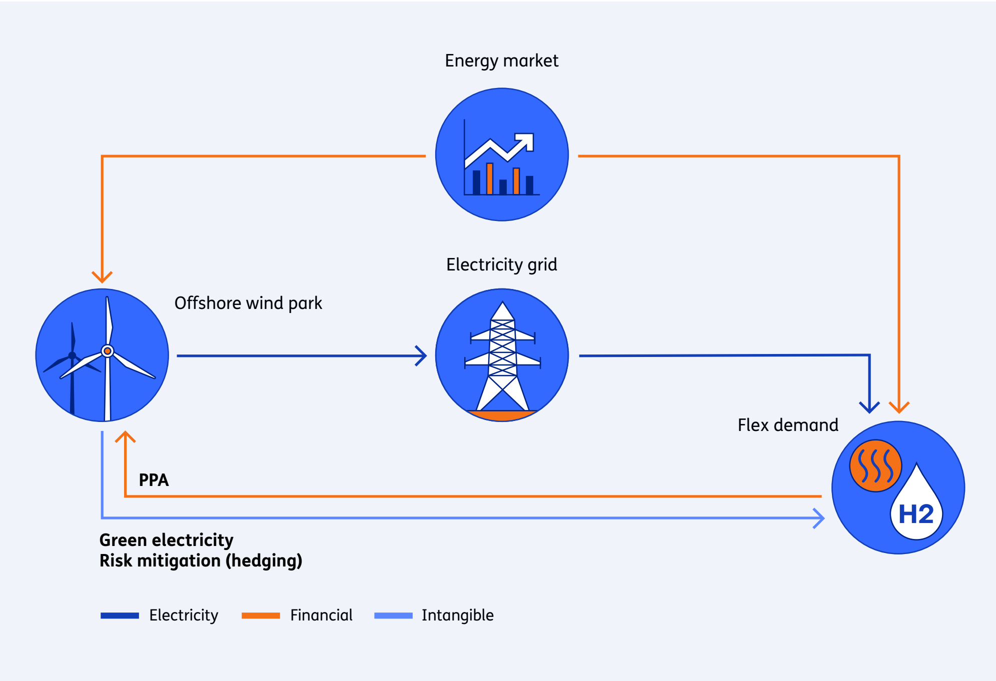

Figure 4. Value network of the integrated business model, including a PPA. The financial value shared with the offshore wind park is met by intangible values (green electricity, price hedging).

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.

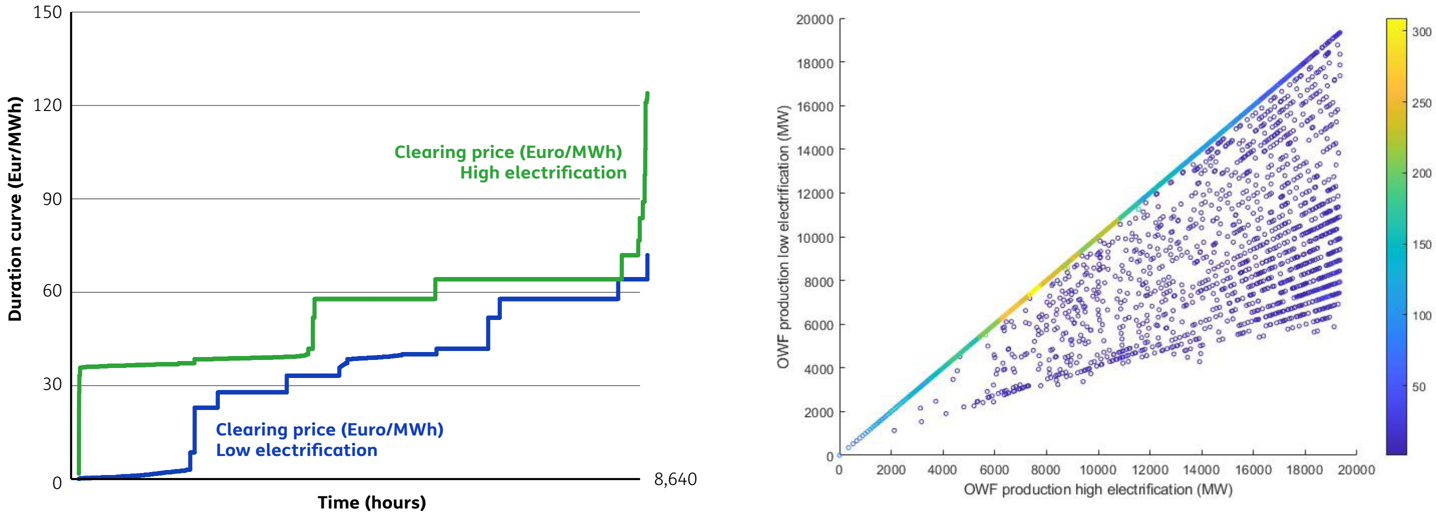

Figure 5. Top: clearing price[6] duration curve for the high-electrification scenario (orange) and low-electrification scenario (yellow). Bottom: scatter plot showing offshore wind production in the high- and low-electrification scenarios (including curtailment) for the full OWF portfolio. Colour bar 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 CO_2-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 CO_2 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 CO_2 prices into account. A positive business case only occurs when CO_2 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 CO_2 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 CO_2 price of €50/tonne). At a hydrogen price of €2/kg and a CO_2 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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Report

Appendices

A Review of policy context

In 2019 the Dutch government laid down greenhouse gas emission reduction goals in the Climate Agreement. These goals aimed for a 49% GHG emission reduction by 2030 compared to 1990 and a 95% reduction by 2050.

Additionally, in 2021, the European Commission presented the Fit for 55 policy package, which delivers stricter GHG emission reduction goals, 55% reduction by 2030 compared to 1990 and a climate-neutral EU by 2050. New and more stringent targets for the Netherlands result in an additional reduction obligation of approximately 15 mega tonnes of CO2 in different sectors such as the built environment, mobility, agriculture, and industry and include a target for green hydrogen use and renewable energy and energy savings.

Furthermore, the proposal of the revised third version of the Renewable Energy Directive (RED III) contains a number of articles with an obligation to use Renewable Fuels of Non-Biological Origin (RFNBO). In the transport sector, the proposal introduces a target of 2.6% (single counted) use of RFNBOs, and a new target for a 50% share of renewables in hydrogen consumption in the industry – including non-energy uses [7].

These new agreements mean that the previously targets for renewable generation in the Climate Agreement for 2030 were based on an expected electricity demand of 120 TWh which, due to more stringent CO2 targets per sector, is expected to increase significantly. Previous work done by [8] describes in more detail the implications of the new reduction targets on extra electrification in the industrial, mobility, built environment and agricultural sectors. For a detailed analysis of sector-specific GHG emission reductions and their effect on the electricity demand for 2030, the reader is referred to [9] for the built environment sector and the study [10] for the mobility sectors. The first advice from the industrial advice group [11] and the recent study from [12] on the REDIII consequences on the Dutch energy demand.

Table 4 summarizes and gives an overview of the estimated extra electricity demand in 2030 for the three emission reduction targets. The 49% target laid out in the Climate Agreement, the 55% target for the Fit for 55 package and the inclusion of the RED III RFNBOs and renewable energy in industrial hydrogen consumption sub-targets.

Electricity demand (TWh per year)	49%	55%	55% + RED III
Electricity demand at the time of Climate Agreement (a)	108	108	108
Extra demand industry 2030 (b)	30.6	50.3	55.6
Direct electricity demand	22.2	29.3	29.3
Electrolyser demand	8.4	21	26.3
Extra demand datacenters 2030 (c)	2.3	2.3	2.3
Extra demand built environment 2030 (d)	8.4	10.5	10.5
Extra demand mobility 2030 (e)	12.4	14.6	27.7
Direct electricity demand	12.4	14.6	14.6
Electrolyser demand			13.1
Extra demand agriculture 2030 (f)	2	2	2
Total electricity demand 2030 (g=a+b+c+d+e+f)	163.7	187.7	206.1
Direct electricity demand	155.3	166.7	166.7
Electrolyser demand	8.4	21	39.4
Electricity demand 2030 in the Climate Agreement (h)	120	120	120
Extra demand (g-h)	43.7	67.7	86.1

Table 4. Overview of the estimated extra electricity demand in 2030 for each of the three reduction targets [8].

B Power market modelling holistic approach

B.1 Power market with increasing flexibility

The equilibrium between electricity demand and supply is determined at wholesale markets, where a pool of power generators bid their production and are awarded a contract until the demand is met. Different markets exist at different time scales. Here, the focus is on the day-ahead market; it is the most representative of electricity markets. The functioning of the market is illustrated via the merit order curve where every asset places a bid for a given capacity and at a specific price, (which equals in theory its variable production costs, driven by the asset technology) [13].

The order of entrance in the merit order curve is as follows: firstly, there are some must-run power plants (e.g. Combined Heat and Power (CHP) units) operating at minimum load supplying energy to the electricity market. After these must-run plants, RES enter with near-zero production costs; then, nuclear plants, fossil-fuelled assets and biomass, which convert energy from an input fuel into power. As such, their variable costs depend on the fuel price, technology characteristics (e.g. conversion efficiencies), operational costs and the European Union Emission Trading System (EU-ETS) CO2 price.

Thus, low variable costs technologies will generally run most of the year at their maximum capacity, and high variable costs assets will mostly operate only for short periods in the year to supply peak demand. At every time-step, the most expensive running asset sets the market price. Besides the electricity demand, the merit order mechanism also includes flexible assets, which act as additional energy demand sources in the electricity market. These are batteries, hybrid boilers and electrolysers (for production of hydrogen). Flexible assets are activated depending on the exceedance of supply over demand and when it is most profitable for them to use the electricity. As variable renewable generation, storage and assets availabilities as well as demand levels fluctuate, so does the merit order structure and thus power market prices. The market drivers are changing and the merit order is also changing during the Energy Transition with the high share of RES penetration (Figure 1)[7]. The main current market drivers and the future expected ones are illustrated in Table 5.

7 The above explanation considers perfect market functioning based on marginal prices and is as such represented in the EYE model.

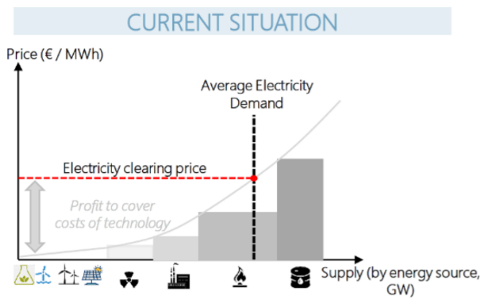
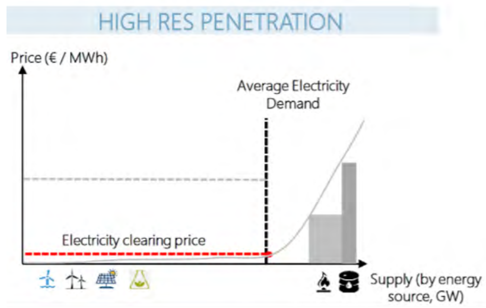
Current market drivers on day-ahead price formation	Factors changing during the Energy Transition
Fossil fuel costs	Energy mix (capacity and costs), hydrogen production at zero marginal cost
EU ETS CO2 prices	Increasing gas and CO2 prices
RES deployment	Increasing RES share
Nuclear and coal decommissioning	No coal, no nuclear
Demand flexibility	Higher demand, electrification (batteries, electrolysers, hybrid boilers, industrial heat pumps, ...)
Interconnection capacity	Higher cross border physical Flows (net exports / imports of each country with the neighbour).
Market setup	Energy trading volume shifts across different channels (PPA/cleared, spot (APX) or exchanged future). Future trends on subsidies schemes (SDE+) feed-in and premium tariffs
	

Table 5. Main market drivers changing in the Energy Transition.

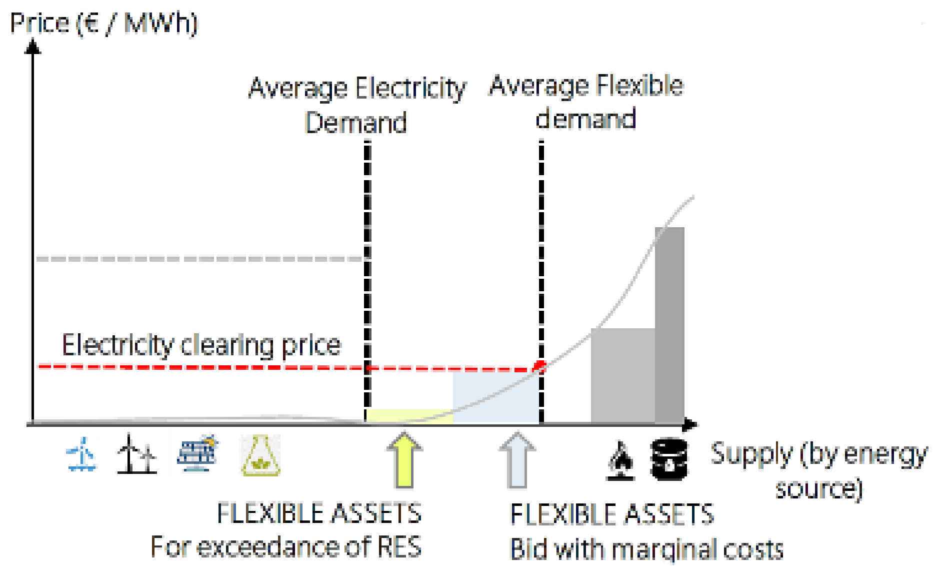


Figure 8. Merit order: impact of RES share in the wholesale market and bidding strategy including flexible assets.

B.2 Holistic modelling setup

The approach consists of a holistic modelling using the European Power Market model,COMPETES, under two scenarios for different rates of electrification, meeting the 2030 RES Dutch targets. A power dispatching tool is then employed to set a range of sensitivities and identify the options for a positive offshore wind farm.

B.2.1 The European Power market model COMPETES

The COMPETES model - COMPetition in Electric Transmission and Energy Simulator is a power system optimization and optimal dispatch model that seeks to minimize the total power system costs of the European power market whilst accounting for the technical constraints of the generation units and transmission constraints between the countries. COMPETES can be used to perform simulations for two types of purposes:

- Least-cost capacity expansion to optimize generation and transmission capacity additions.
- Day-ahead markets, through least-cost planning and dispatch of generation and demand

The COMPETES model covers 27 EU Member States and some non-EU countries (i.e., United Kingdom, Norway, Switzerland, and the Balkan countries), including a representation of the cross border transmission capacities interconnecting these European countries. Every country is represented by one node, except Luxembourg, which is aggregated to Germany. The Balkan and Baltic countries are each aggregated in one node. The model assumes an integrated EU market where the trade flows between countries are constrained by 'Net Transfer Capacities (NTC) reflecting the Ten Year Network Development Plan (TYNDP) of ENTSO-E. The model has time steps of one hour. In this study, the target years of the scenario cases are optimized over all 8,760 hours per annum.

Over the past two decades, COMPETES has been used for many assignments and studies on the Dutch and European electricity markets. Also, it is used and regularly updated as part of the energy modelling framework for the annual Climate and Energy Outlook of the Netherlands, see also [14] for other uses and applications of the COMPETES model. This brief description focuses on the Netherlands' application and the rest of Europe. The description is limited to a general summary of the main elements of the model.

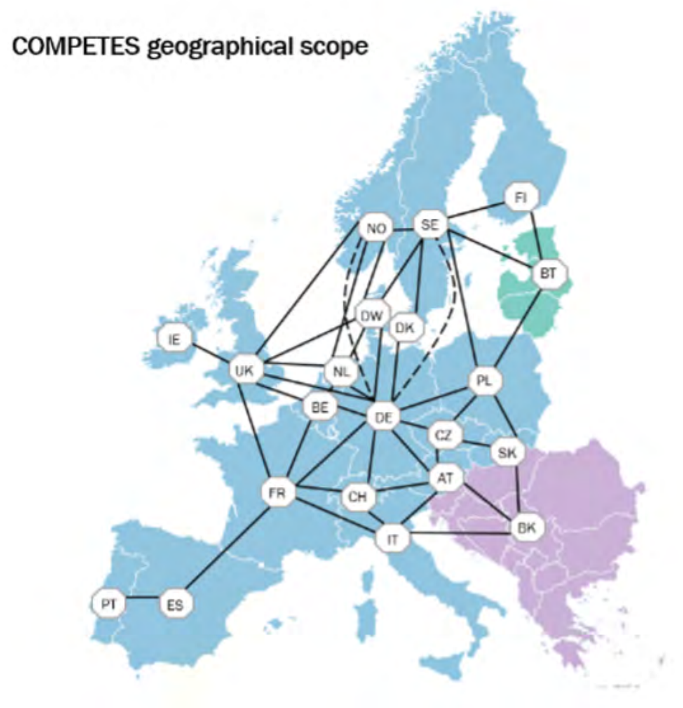


Figure 9. Cross border connections of the COMETES power market model.

B.2.2 Electricity supply

The input data of COMPETES involves a wide range of generation technologies. There are 14 types of fossil-fuel fired power plants – which can operate with CCS or as a combined heat and power (CHP) plant –nuclear, geothermal, biomass, waste, hydro, wind and solar technologies. In particular, detailed out with unit by unit generation in the Netherlands. The units using the same technology and having similar characteristics (i.e., age, efficiencies, technical constraints, etc.) are aggregated for the other countries.

B.2.3 Inputs/outputs

The main inputs for electricity supply options can be summarized as:

- Operational and flexibility characteristics per technology per country.
- Efficiencies.
- Installed power capacities.
- Availability (seasonal / hourly).
- Minimum load of generation and minimum load costs.
- Startup / shutdown costs.
- Maximum ramp-up and down rates.
- Minimum up and downtimes (only for the units in the Netherlands).
- Emission factors per fuel/technology.
- Fuel prices per country, ETS CO2 price, (national CO2 tax).
- Hourly time series of VRE technologies (wind, solar etc.).
- Overnight costs for conventional generation (Euro/MW).
- Transmission capital expenditures (CAPEX; Euro/MW).

The COMPETES model calculates the following main outputs for the EU28+ as a whole as well as for the individual EU28+ countries and regions:

- Investments in cross-border transmission (interconnection) capacities (capacity expansion module output).
- Investments in conventional generation capacities (capacity expansion module output).
- The allocation of power generation and cross-border transmission capacity.
- Hourly and annual power generation mix – and related emissions – in each EU28+ country and region.
- The supply of flexibility options, including power generation, power trade, energy storage and VRE curtailments.
- Hourly competitive electricity prices per country/region.
- Power system costs per country/region.
- VRE curtailment resulting from unit commitment and economic dispatch.

Hourly VRE time series

The used dataset provides hourly PV capacity factors for the EU-27 plus Norway and Switzerland, simulated with MERRA-2[8] and CM-SAF SARAH[9].

Similarly, hourly wind capacity factors are calculated for the EU-27 plus Norway and Switzerland, based on MERRA-2, simulating the present-day fleet of wind farms, the near-term future and future long-term fleet. Detailed information on datasets in [15].

8 The Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) is a global atmospheric reanalysis produced by the NASA Global Modeling and Assimilation Office (GMAO).
9 The Surface Solar Radiation Data Set - Heliosat (SARAH) is a satellite-based climatology of the solar surface irradiance.

Results from the COMPETES simulations for two scenarios (high versus low electrification) in 2030

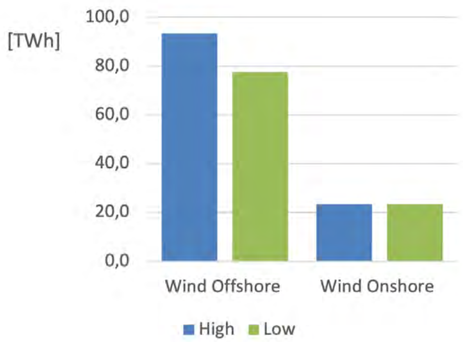


Figure 10. NL wind generation

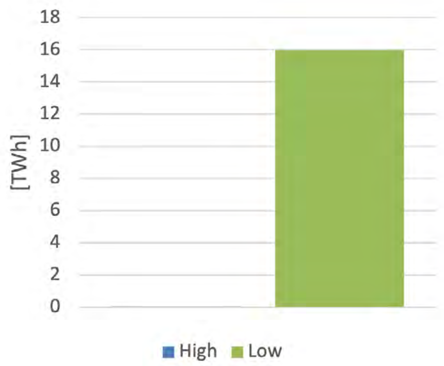


Figure 11. NL wind curtailment

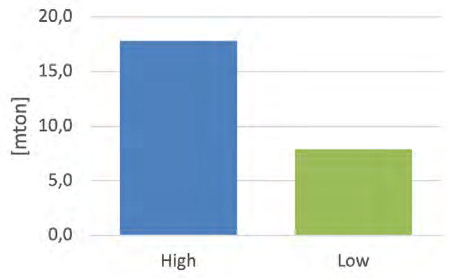


Figure 12. NL power system CO2 emissions

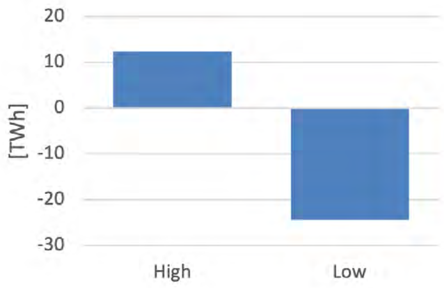


Figure 13. NL net trade

Wind offshore and onshore generation and curtailment

Curtailment – In the high electrification scenario curtailment is almost negligible (0.01%), while the lower scenario shows 16 TWh of curtailed offshore wind. This is explained by the absence of flexible assets and lower electricity demand in the Low case. Once there is Power-to-heat in industry and power-to-hydrogen technologies that can shift their demand, more wind offshore can be accommodated in the system. From the offshore wind view, in the low demand scenario there is not enough flexible demand to supply with the 21.5 GW built. However, there is still potential for higher electrification of industrial sector which is not yet electrified. Under this scenario, the curtailment of wind could be translated into decoulpling integrated systems to supply direct power under PPA contracts. In the high electrified demand scenario, the results are in favor of offshore wind business because it is 100% utilized in an electrified system

B.3 The EYE power market model for business cases

The EYE model is a power market simulator capable of assessing the effects on energy prices in the day ahead market based on different sources of supply, expected demand, marginal costs, prices that are defined by individual assets that make up an intended energy system. Within an energy system, each asset can be defined based on its technology, efficiencies, marginal costs, fuel sources or generation profiles. This allows for the analysis of a specific asset's performance and behaviour in the market under imposed system level conditions or scenarios.

The EYE model is developed to model the future electricity grid and flexibility options based on first order estimations, in order to study complex system effects quickly. It gives the end-user the ability to change parameters and explore effects with a user interface easily. EYE can be used to analyse specific business cases, as well as nationwide electricity grids. Lastly, EYE is meant to be as open and transparent as possible, showing which assumptions and calculations are made [16].

A visual representation of the model is presented in the Figure 14.

From the customizable assets that represent the inputs to the EYE model, price clearing mechanisms are then established for supply and demand based on a merit order raking of marginal costs for each hourly time step.

The intersection of supply and demand merit orders, along with their bidding volumes determines the clearing price for the electricity market for each time step. Further theoretical and methodological explanations of the EYE model, along with asset descriptions and specifications can be found in [16].

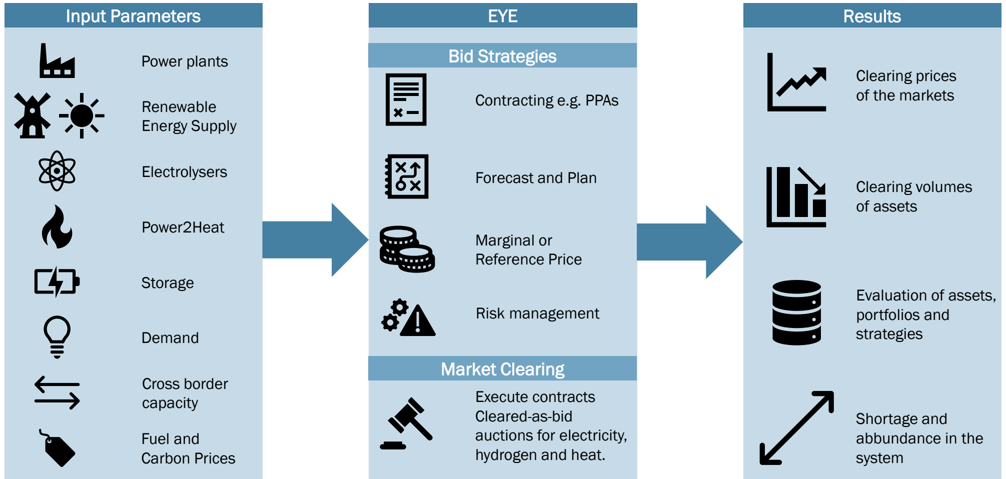


Figure 14. Overview of EYE simulator with inputs: models of demand and supply bid behavior, and outputs such price and production/consumption profiles of individual assets [16].

B.3.1 EYE model configuration for flexible assets

Within the EYE model, the demand merit order profile is dominated primarily by static electricity demand that must always be met, along with flexible assets that can enter the market if the conditions to buy electricity are beneficial for their operation. The model [16] obtain future electricity prices and the merit order effect.

Flexible assets have the ability to change the merit order of the demand profile and therefore can play an important role in determining the electricity market price. These types of assets, such as hybrid boilers, heat pumps, electrolysers, batteries, etc., bid into the market with an activation price, which is a price based on their efficiencies, emission costs, and possible fuel source that is the produced from the asset and envisioned to be sold in another market. If the proposed electricity price is below a flexible asset's activation price, the asset will consume electricity, and participate in the market for the time step of interest. Table 6 presents some technical specifications of different flexible assets that were considered in this study.

Asset	Efficiencies	Symbol	Values
Heat Pumps	COP	COP	3
	Boiler Efficiency	n_{Boiler}	0.9
	Heat Pump Efficiency	n_{HP}	1
Hybrid Boilers	Boiler Efficiency	n_{Boiler}	1
	Vapour Factor	n_{Vapour}	1
	Reference P2X Efficiency	n_{P2X}	0.9
Electrolysers	Efficiency	n_{H2}	0.67
	SMR efficiency	n_{SMR}	0.72
	SMR CO2 emission factor	$CO2_{Emisstion\_SMR}$	0.27
Natural Gas	Natural CO2 emission factor	n_{NGC}	0.2

Table 6. Asset Technical Specifications.

These specifications are used in the following equations to determine the activation price (or bidding price) of the flexible assets. They are based on the chosen fuel type, their associated costs, efficiencies, and CO2 emissions. The CO2 price was set to that modelled in COMPETES, to a value of 57.6 Euro/tonne.

The activation price for heat pumps is defined in Equation 1 as:

$$\text{Activation Price}_{HP} = \text{COP} * (\text{Fuel Cost} + \text{CO2}_{Emisstion} \times \text{CO2}_{Price}) \times)n_{HP} / n_{Boiler}) \tag{1}$$

The activation price for hybrid boilers is defined in Equation 2, 3 and 4 as:

$$\text{Fuel Price}_{HB} = (\text{Fuel Cost} \times n_{Boiler}) / (n_{P2x} \times n_{Vapour}) \tag{2}$$

$$\text{CO2 Price}_{HB} = (\text{CO2}_{Emisstion} \times \text{CO2}_{Price}) \times (n_{Boiler}/n_{P2X}) \tag{3}$$

$$\text{Acitivation Price}_{HB} = \text{Fuel Price}_{HB} + \text{CO2 Price}_{HB} \tag{4}$$

Finally, the activation price of electrolyzers are based on a presumptive price of SMR based hydrogen production as described in Equation 5:

$$\text{Activation Price}_{H2} = ((\text{Fuel Cost}_{Natural\ Gas} / n_{SMR}) + (\text{CO2}_{EmissionSMR} \times \text{CO2}_{Price}) / n_{SMR})) \times n_{H2} \tag{5}$$

Within the EYE model, assets can vary the quantity that they supply or demand to or from the market over a range of bidding prices. Assets also can be run in a similar way to the static electricity demand, hence in a "must run" specification. These operational strategies can influence the involvement of assets in the market, by changing the merit order profiles of either the supply and demand. This in turn may influence the market clearing electricity prices over the simulations period.

B.3.2 Calibration EYE model with the COMPETES model

The COMPETES model presented in previous chapter provides a system level overview of the expected energy mix of supply and demand, influenced by existing and recently revised policies and targets for the 2030 Dutch energy system. These policies and targets formed the bounds of high and low electrification scenarios. In COMPETES, the electrified flexible assets were configured to run in baseload operation (along with the static electricity demand) in order to ensure that the flexible demand side targets were covered by the supply (including imports).

The goal of this chapter is to represent the proposed scenarios of high and low electrification as modelled in COMPETES, but through the perspective of the EYE model. More specifically, the same sources of supply will be modelled in order to meet the same desired quantity of targeted demand, both as static and flexible. Assumed inputs and resulting outputs of the Competes model were used to establish the desired scenarios in EYE. The establishment of a calibration between EYE and COMPETES, considering these assumptions and understanding its limitations, will form a baseline for each electrification scenario on which the business case of a particular offshore wind asset can be further explored and investigated.

In order to create a model that is representative of COMPETES in EYE, the input sources of supply had to be modelled to meet a fully static demand at first (which is the output of COMPETES). The following methodology was followed to establish the appropriate supply side features:

1. Fuel costs, CO2 Emission costs, and market constraints were represented in EYE. The maximum market price was set to 300 Euro/MWh (above all generating and consuming assets in the market), and the minimum was set to 0 Euro/MWh (not allowing for negative prices to occur in the market.
2. The capacities of each renewable supply source as modelled in COMPETES were represented as assets in EYE. Assets for renewables were modelled as one large cluster for each type (solar, wind, offshore wind) with their respective target capacities envisioned for 2030.
3. The renewable energy assets were provided with representative normalized production profiles that COMPETES used as an input. These profiles respect a targeted level of full-load hours over the simulation year.
4. The cumulative capacity of fossil fuel and power plant modelled in COMPETES were tabulated, along with their average marginal cost.
5. Virtual power plants with representative marginal costs were then modelled as assets in EYE, such that the marginal cost profile of these power plants were respected for the industry. Fossil based plants, hydro converted plants, and other were considered in the make-up of these virtual plant assets.

The following Table 7 summarized the quantity of supply modelled in COMPETES and in EYE.

Source	Capacity (GW)	Marginal Cost (Euro/MWh)
Solar	25.25	0.0
Onshore Wind	7.22	1.5
Offshore Wind	21.5	2 – 2.1
Fossils and Others	15.5	20 to Over 100+
Nuclear	0.46	9.2

Table 7. Summary of supply sources considered in EYE taken from the COMPETES model.

With the supply defined as representative assets in EYE, the demand was then established, and first considered as entirely static. This was done to force the entire demand in EYE and ensure that the supply could provide all the energy required, thus establishing a calibrated baseline of the COMPETES model in EYE. The following approach was followed:

1. Normalized profiles, on an hourly time step, were created considering the resulting static demand, flexible demand, imports and exports resulting from COMPETES.
2. The normalized profile was scaled to the total energy demand.

Once the COMPETES model was represented in EYE, the flexible demand assets modelled originally as part of the static demand was made free to operate as proper flexible assets represented in EYE. In doing so these flexible assets (with their respective capacities and sizes) can now bid into the market and establish the demand side merit order curve. These demand-side flexibility assets enter the market only if their bidding prices (their activation price) is higher than the clearing price. This results in similar or less demand than in the COMPETES representation. The COMPETES based model represents a world where all these assets are turned on around the clock. However, with EYE, it is now possible to explore the effects of flexibility as these assets join the electricity market as marginal-price -driven actors.

The following approach was followed to model the different flexible assets in EYE:

1. Assets were modelled with their respective peak capacities, which could be derived by the demand profiles from COMPETES.
2. Assets that are not properly captured yet in EYE, such as EV's, were modelled as another asset, in this case a separate hybrid boiler. The reason for this was to have a simple demand asset that would act as a sink for energy to be dispatched to. EV's in this study are not the emphasis of the analysis, but future work should improve the dynamics of such an asset to be more representative its real-world operation.
3. The static demand profile was normalized to include the base Dutch electricity, imports, and exports resulting from the COMPETES model. This profile was scaled to the representative energy modelled in COMPETES over the simulation year for each scenario. Note that the COMPETES profiles considered represent the interaction cross-border under the assumption that flexible demand in NL is not flexible but demand around the clock. If these assets are not activated at a certain point in time, this can mean that the import/export is reduced.

Source	High electrification (TWh)	Low electrification (TWh)	*Full Load Hours [High, Low]*
Static Demand	120.3	124.5	-
Imports	42.3	25.9	-
Exports	30.0	50.4	-
Static minus net import/exports	108.0	148.9	-
Hydrogen (Electrolysers)	39.4	0.4	[3500,4307]
Heat (Hybrid Boilers)	24.9	0.0	[3500,0]
Heat Pumps	13.9	2.5	[1509,1509]
Electric Vehicles	14.7	3.3	[2409,2250]

Table 8. Range of electrification targets of COMPETES results.

Table 8 below presents the yearly demand values that were used to scale the normalized profiles modelled as inputs to the electricity demand in the EYE model. Also included are the amount of flexible demand targets in each scenario.

Finally, the last step of the demand side calibration process was to generate the proper quantity of each flexible asset. This was done under the following possible options:

1. The size (capacity) of flexible assets could be reduced, if the modelled peak capacity to start generates too much flexbile demand compared to the target yearly values output in COMPETES. Reasons for this is that flexible assets in EYE bid into the market based on their marginal price, establishing a merit order that can allow it to enter entirely or to not participate. If an asset was able to always participate due to it's high value marginal price, then it would always remain in the market requesting it's peak capacity, hence leading to more demand than a modelled profile that is demanded in COMPETES.
2. "Must Run" conditions (where an asset will demand energy at any price to meet its target capacity, thus entering the market before all other flexible assets) could be enforced on flexible assets to ensure that a certain amount of generation was always produced. In COMPETES, the flexbile assets such as electrolysers and hybrid boilers were entirely forced as baseload demand, where in EYE, a portion of this demand can be made flexible or "must-run".

A starting point was established in which the flexible assets were free to demand electricity simply based on their marginal price without any "must run" conditions imposed. For certain assets such as heat pumps and EVs, modelling the peak capacity of their COMPETES profile lead to more demand supplied to those assets. This could be that the peak was not representative of the most common levels of production for that asset. In the case of heat pumps, the average of the timeseries was used, and since it is a flexible asset with a high activation price, it would also be producing heat at an average value such that the year demand was reached.

Table 9 shows the results of the "Free-Flex" conditions, and it is possible to observe in the High electrification scenario that there is not enough flexible demand generated, hand in hand with less gas supply by an equivalent amount. The Low electrification scenario has too little amount of flexible demand, and the proper amount of generation is in line with COMPETES. This can be seen as an intermediate step towards the final calibration.

Following the "Free-Flex" results, "must-run" constraints on the electrolysers and hybrid boiler assets then were applied, ensuring that a portion on their capacity was always met from the available supply (hence operating under partial "must-run" conditions). These asset could therefore demand a portion of their energy before other flexible assets, and obtain the rest of their demand following the regular demad merit order establishment based on marginal price.

Table 10 presents the calibrated results of the EYE model under "must-run" conditions to the COMPETES supply and demand targets for each scenario considered. It is now possible to see that the COMPETES flexible demand is adequately represented in EYE. This is taken as the baseline for the remaining analyses stemming from thisa report.

	High electrification		Low electrification		
Model	COMPETES	EYE	COMPETES	EYE	Unit
Average Clearing Price	55.4	45.7	32.5	35.7	Euro/MWh
Onshore Wind	23.5	23.5	23.5	20.9	TWh
Offshore Wind	93.5	93.5	77.6	82.3	
Solar	26.9	26.9	26.9	26.4	TWh
Total Wind	117.0	117.0	101.0	103.2	TWh
Total Renewable	143.9	143.9	128.0	129.6	TWh
Total Fossil + others	52.9	25.7	24.4	20.7	TWh
Total Nuclear	4.0	4.0	2.7	3.3	TWh
Total supply	200.8	173.7	155.1	153.6	TWh
Dutch Static Demand [A]	108.0	108.0	148.9	148.9	TWh
Electrolysers	39.4	13.4	0.4	0.4	TWh
Hybrid Boilers	24.9	25.3	0.0	0.0	TWh
Industrial Heat Pumps	13.9	13.9	2.5	2.5	TWh
EV	14.7	15.0	3.3	3.4	TWh
Total Flexible	92.8	67.7	6.3	6.3	TWh
Total Demand	200.8	175.7	155.1	155.2	TWh
A. Less Net Imports/Exports.					

Table 9. EYE Compared to COMPETES Targets, Electrification Scenarios – "Free Flex" Conditions.

	High electrification		Low electrification		
Model	COMPETES	EYE	COMPETES	EYE	Unit
Average Clearing Price	55.4	53.7	32.5	35.7	Euro/MWh
Onshore Wind	23.5	23.5	23.5	20.9	TWh
Offshore Wind	93.5	93.5	77.6	82.3	TWh
Solar	26.9	26.9	26.9	26.4	TWh
Total Wind	117.0	117.0	101.0	103.2	TWh
Total Renewable	143.9	143.9	128.0	129.6	TWh
Total Fossil + others	52.9	52.4	24.4	20.7	TWh
Total Nuclear	4.0	4.0	2.7	3.3	TWh
Total supply	200.8	200.4	155.1	153.6	TWh
Dutch Static Demand [A]	108.0	108.0	148.9	148.9	TWh
Electrolysers	39.4	38.9	0.4	0.5	TWh
Hybrid Boilers	24.9	24.2	0.0	0.0	TWh
Industrial Heat Pumps	13.9	13.9	2.5	2.5	TWh
EV	14.7	14.3	3.3	3.4	TWh
Total Flexible	92.8	91.3	6.3	6.3	TWh
Total Demand	200.8	199.3	155.1	155.2	TWh
A. Less Net Imports/Exports.					

Table 10. EYE Compared to COMPETES Targets, Electrification Scenarios – Must Run Conditions.

Asset	EYE - High Scenario (TWh)	EYE - Low Scenario (TWh)	Capacity (GW) [High, Low]	FLH [High, Low]	Minimum Load [High, Low] (%) [A]
Onshore Wind	23.5	20.9	7.22	[3255,2891]	-
Offshore Wind	93.5	82.3	21.5	[4348,3827]	-
Solar	26.9	26.4	25.25	[1065,1045]	-
Electrolysers	38.9	0.5	[11.257, 0.1]	[3455,5000]	[35, 10]
Hybrid Boilers	24.2	0.0	[7.1, 0.0]	[3408,0]	[8.5, 0]
Industrial Heat Pumps	13.9	2.5	[1587, 0.285] [C]	[8760,8760]	-
EV [B]	14.3	3.4	[4.2, 0.738] [B]	[3404,6465]	[8.5, 0]

A. *Expressed as the percentage of the modelled capacity presented in this table.*
B. *EVs were modelled as a hybrid boiler asset, as EYE is not yet adapted to model EV storage. The capacity was reduced from the COMPETES generated profile output, for calibration purposes (over supply).*
C. *Heat Pump capacity was reduced to the average of the the COMPETES profile output, for calibration purposes (over supply).*

Table 11. Resulting capacity, full-load hours and minimum loads of assets in EYE.

Table 11 shows the amount of minimum load ("must-run" capacity) that each flexible asset was assigned in order to generate the target demand in each scenario, along with the capacity of each asset used, and their resulting full load hours. It also provides the full load hours of the variable renewable energy supply modelled.

Furthermore, the resulting price duration curves of the resulting EYE baselines considering "Must-Run" conditions and the "Free-Flex" conditions of flexible assets are compared in the COMPETES price duration curve Figure 15. The difference in the Low EYE scenarios are insignificant due very small amounts of flexible demand required. Both EYE Low scenarios align relatively well with the LOW COMPETES Scenario. As for the High EYE scenaiors, more notable differences can be seen at the low end of the price profile. This is due mainly to the import of supply from different sources cross border that are not represent in EYE on the supply side (and rather included in the static Dutch electricity demand profile).

The resulting summary table and clearing price duration curves presented above are based on the calibration approach of imposing a certain portion of the capacity of the flexible assets as "must run in" the market (as described in the methodology above). Once assets are made flexible in the EYE model, their activation price will dictate whether it is profitable to enter the market to receive electricity from the remaining supply. However, without imposing a minimum capacity to be "forced" the flexible assets do not generate the targeted demand.

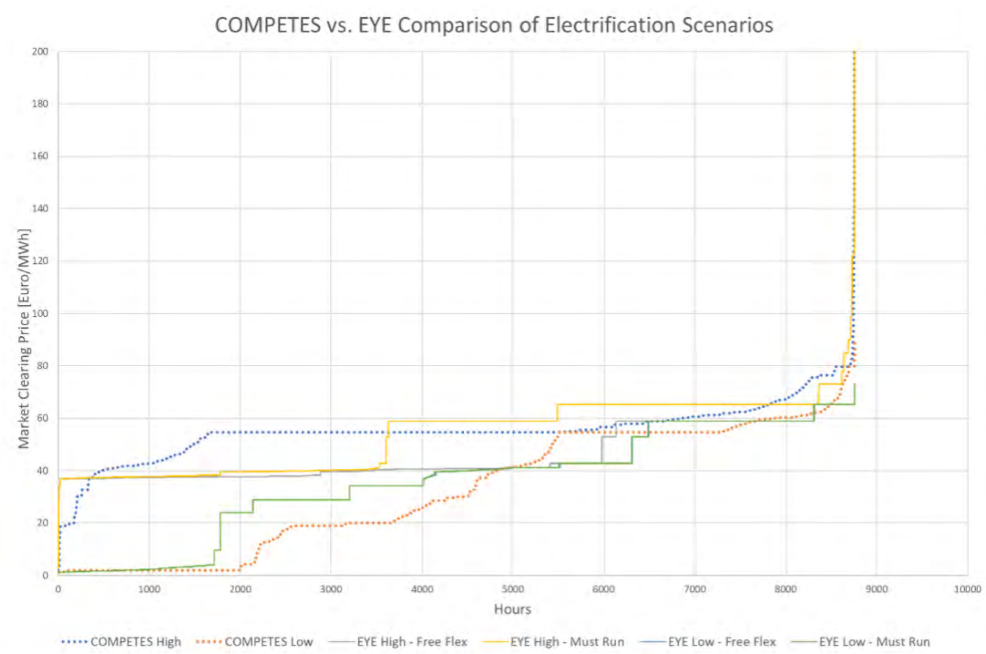


Figure 15. Price duration curves of COMPETES (dashed) and EYE (solid colours, “must run” or “Free Flex” operation of flexible assets) for high and low scenarios.

B.3.3 Sensitivities Conducted for PPA investigations

Based on the baseline represented in the EYE model for both the High and Low electrification scenarios, sensitivities can then be further conducted to assess the business case of an offshore wind farm under different conditions.

It was determined to investigate the choice between an offshore wind farm delivering power to the market, to a hybrid boiler (hence a power to heat PPA), or to an electrolyser (hence a Power to Hydrogen PPA). To do this, a matrix of varying hydrogen reference prices, and CO2 prices were investigated for all scenarios (free flex and minload in both high and low electrification conditions).

For the analysis of the low scenarios, the baseline conditions did not consider enough hydrogen production via electrolysis nor heat production by hybrid boilers given the low amount of flexible demand targets. Therefore, a virtual asset of either a hybrid boiler or electrolyser with the same capacity as the chosen 2 GW offshore wind farm under investigation was added to the model and simulated under the varying hydrogen and CO2 prices. Given that the low electrification had a large amount of curtailment of offshore wind due to inadequate demand, increasing the flexible demand of that particular asset by such a capacity chosen would not impact the overall market structure.

C Long term business case of offshore wind

The expected installed capacity of offshore wind in the two scenarios (21.5 GW) – low and high electrification - is divided into two parts, a larger offshore wind farm cluster of 19.5 GW and a smaller wind farm of 2 GW. The reason for this division in offshore wind farm capacity is to estimate potential differences in business case for wind farms bidding at different marginal costs in the merit order.

C.1 Business model

A simplified business case is analyzed for: offshore wind, elektrolysers, hybrid boilers and industrial heat pumps. The analyzed business models are as follows:

- **Offshore wind:** Conducts and investment in offshore wind farms and operates/maintains these farms. The produced electricity is sold to the electricity market or by PPA to a flexible asset.
- **Electrolysis:** Conducts an investment in an electrolyzer and operates/maintains this asset. The electrolyzer buys electricity from the market or through a PPA from the offshore wind farm. The hydrogen produced by the elektrolyser is sold. The hydrogen price can be based on the reference of an SMR which uses natural gas to produce hydrogen, or on a hydrogen market price.
- **Boilers/Heat pumps:** Conducts an investment in a Power-2-Heat asset and operates/maintains this asset. The asset buys electricity from the market or through a PPA from the offshore wind farm. The heat produced by the asset is used to avoid heating with natural gas using a gas boiler. The reference price of this heat is based on the natural gas and CO2 price.

The business analysis consists of comparing the business model where all assets clear on the market compared to a business model where certain flex assets have a PPA with the offshore wind farm. There are several drivers behind constructing a PPA, based on [5]:

- Offshore wind developers creating a strong pipeline of projects to secure a route-to-market.
- Government can reduce support schemes when renewables can compete with market prices.
- Offshore wind developers reduce risk from exposure to longer term price fluctuations.
- Offtakers achieve recognition for using renewable energy and unlock value when PPA's beat market prives.

This study will focus on the value of PPA's in hedging price fluctuations both for offtakers and offshore wind developers. Two main PPA constructions can be distinguished [6]:

- In the virtual PPA model, the power producer sells the generated electricity into the wholesale power market. The payments received by the power producer from the fluctuating wholesale power price are net-settled9 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 physical PPA model, there is a physical network connection between the generation asset and the load of the corporate buyer. The generated electricity is nominated with the system and/or market operator to be delivered to the corporate buyer's point of consumption via the electricity network. This allows for direct delivery of power from the power producer to the corporate buyer. The corporate buyer usually purchases any additional power needed to serve the remainder of the load via its existing retail electricity provider or a third-party.

In this analysis the virtual PPA model is be analyzed through the impact on the clearing volumes of the EYE market model. The two analyzed business models are visualized in Figure 16 and Figure 17.

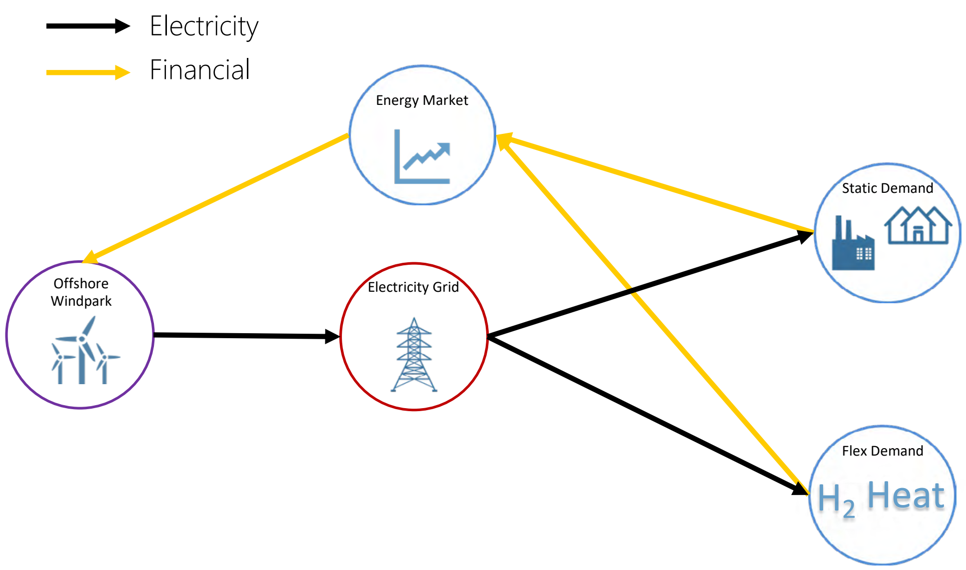


Figure 16. Base business model where all assets operate solely through the wholesale electricity market.

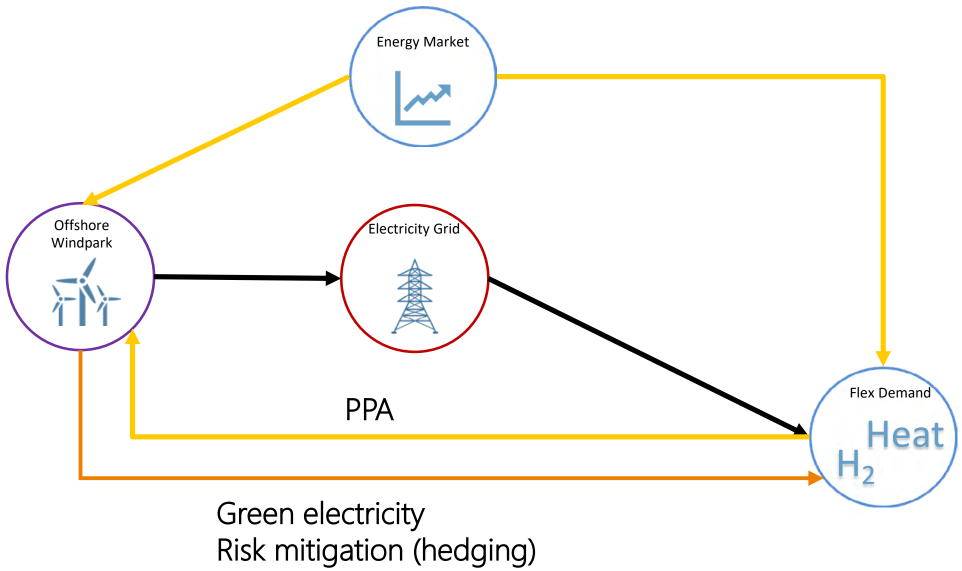


Figure 17. VPPA business model, where the offshore windpark has a virtual PPA contract with a specific flexible demand asset.

C.2 Assumptions

The following assumptions on CAPEX, OPEX, prices and O&M have been used in the business case modelling. In Table 12, the assumed CAPEX are shown, which includes an assumed installation factor. The installation factor for offshore wind is based on study results by TNO and Blix [4] [17]. For hybrid steam boiler and industrial heat pump it is based on several use cases in which the integration costs are higher for heat pumps because of the waste heat demand.

The assumed O&M per technology is shown in Table 13, the Heat Pumps have the highest assumed O&M because this is a technology with moving parts, which is subject to higher maintenance cost.

In Table 14, the financial assumptions of the business case are shown. The time horizon of the case is taken to be 25 years, based on the economic lifetime of offshore wind farms. The Weighted Average Cost of Capital (WACC) represents the rate that the companies have to pay for financing the assets. In general, the WACC in an industrial setting is higher compared to the WACC in an energy production setting.

Following the business model, in some cases the revenue is based on avoiding a natural gas based alternative. To this end the business case assumes the efficiency of the electrical assets and the alternatives, as shown in Table 15.

The commodity prices as used in the baseline business case are shown in Table 16. These prices are varied in the sensitivity analysis.

Technology	CAPEX (€/MWe)		Installation factor
Electrically driven heat pump [18]	€	2,250,000.00	3
Hybrid electrical steam boiler [19]	€	120,000.00	2
Electrolyser (TNO)	€	820,000.00	2
Offshore wind [17]	€	2,566,000.00	1.6

Table 12. CAPEX assumptions.

Technology	O&M (% of CAPEX)
Electrolyzer	2%
Heat Pumps (use cases)	5%
Electric Boiler [19]	2%
Offshore wind [17]	2%

Table 13. OPEX Assumptions.

Financials	
Time Horizon	25
WACC - Demand assets	8%
WACC - Supply assets	4%

Table 14. Financial assumptions.

Asset	Efficiency	Alternative	Alternative efficiency
Electrolyzers	67%	SMR	72%
Electrical steam boiler	99%	Gas boiler	90%
Electrical driven heat pump	300%	Gas boiler	90%

Table 15. Asset and alternatives efficiencies.

Commodity	Price (Baseline)		Unit
Natural Gas		25	€/MWh
CO2	€	57.60	€/ton

Table 16. Commodity prices in the baseline scenario.

C.3 PPA Implementation

The PPA implementation is added as a post-processing step to the modelling. No changes are made in the EYE modelling. Consequently, the PPA has no effect on the system and the operation of other assets. Both the offshore wind asset and the flexible assets (electric boiler and electrolyser) bid based on their marginal costs. Whenever the clearing price is **higher** than the bidding price of offshore wind, the offshore wind asset will be on. Whenever the clearing price is lower than the bidding price of the flexible assets, they will be on. The bidding price of offshore wind is **lower** than the bidding price of the flexible assets. The operators of the offshore wind and flexible assets need to determine a PPA price. This will be part of negotiations. We do not try to estimate what a good or fair PPA price should be, instead we model the integrated business case of an offshore wind and flexible asset.

At any hour, both the offshore wind and flexible asset have a clearing volume. The minimum of these volumes is what will be traded via the PPA. If the offshore wind has a remaining clearing volume, then it sells this on the market, at the clearing price of the market. If the flexible asset has a remaining clearing volume, then it buys this on the market, at the clearing price of the market. So, if the offshore wind asset has a clearing volume of 1,500 MWh and the flexible asset has a clearing volume of 2,000 MWh, then all of the offshore wind energy (1,500 MWh) will be used in the PPA. The flexible asset buys the remaining 500 MWh on the market.

The PPA and remaining volumes are calculated by doing this for every hour and summing over the year. The capture price of the assets are only calculated for the remaining parts. This is done by calculating the weighted average of the clearing price, using the remaining volumes for each hour as weights. Effectively, the capture price of the PPA volume is equal to the PPA price. For the offshore wind asset this is a revenue, while it is a cost for the flexible asset. In the integrated business case these cancel each other.

C.4 Baseline Results

The analysis follows a simple business model, omitting infrastructure cost and using highly uncertain market prices. Therefore the results should be interpreted as trends and not as investment analysis.

The baseline results comprise of an analysis of the high electrification and low electrification scenario's. The business case analysis has been conducted on two operational strategies of the flexible assets:

- minLoad: In this strategy, the flexible assets are imposed with a minimum load that has to be satisfied. This minimum load is based on the scenario results from COMPETES and reflects the targets from REDII. This strategy will mean that assets will also bid in the market at times that this is not profitable.
- FreeFlex: In this strategy, the flexible assets are free to bid on their marginal price. Therefore they will only bid in the market at times that this is profitable. However this strategy does not guarantee that the REDII targets are met and the results will differ from the COMPETES output.

First discuss the results of S1 and S3 will be discussed, after which the impact of the operational strategy will be described.

The results of the business case in S1 and S3 are shown in Figure 18 and Figure 19. In the low electrification scenario there are no electrical steam boilers assumed in the system, therefore these do not show in the results. Furthermore, in the high electrification scenario, the IRR of electrolyzers can not be calculated as the cash flow is negative.

The business case results show that the high electrification scenario is profitable for the offshore wind farm, with an IRR of 5%. However, this scenario has a worse performance for flexible assets, electrolyzers and electrical steam boilers have a negative cashflow. The industrial heat pumps are profitable in each scenario, this is because these assets profit from a high COP and therefore act as if they are baseload, profiting from low prices.

In the Low electrification scenario the envisioned amount of offshore wind is not profitable, and will even be curtailed in some hours of the year.

The business case of flexible assets improve, as they are a scarce resource in this scenario. The IRR of heat pumps increase with 12% in this scenario and the NPV of electrolyzers increasing with €1 mln.

Concluding, the business case of offshore wind is supported by increased electrification. However, this has a drawback on the profitability of the electrification assets in the system, which will not have a positive case for investment if there are no additional stimulations.

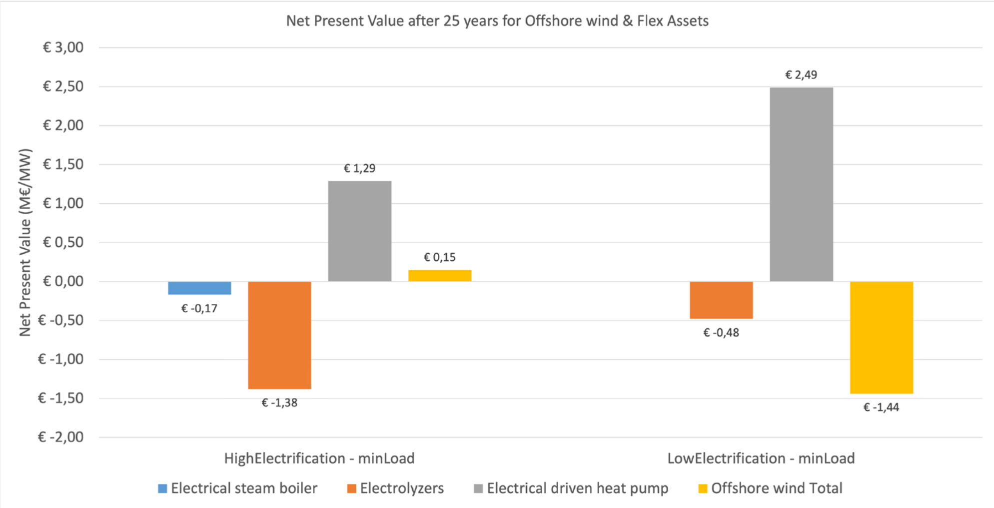


Figure 18. Net present value after 25 years for offshore wind & flex assets in S1 and S3.

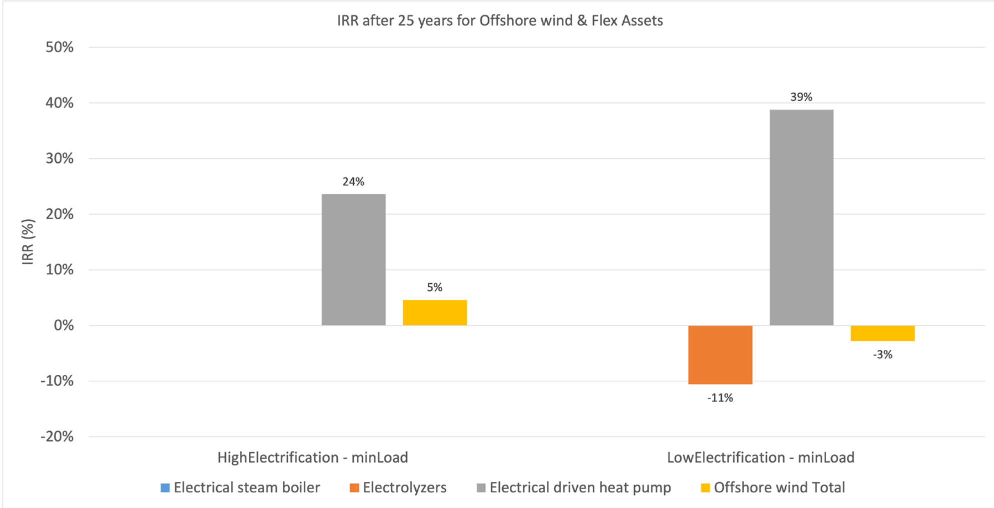


Figure 19. Internal Rate of Return after 25 years for offshore wind & flex assets in S1 and S3.

In Figure 20 and Figure 21, the business case results are shown in the high electrification scenario with the FreeFlex and the minLoad strategy. What can be seen is that the FreeFlex strategy has a positive impact on the business case of the flexible assets, these will run at more profitable hours when compared to the minLoad strategy. This does have a negative result on the offshore wind assets, as the capture price lowers with 7 €/MWh due to less baseload being bid in the market.

Sensitivity analysis has been performed on the offshore wind business case by changing the CO2 and H2 prices:

- CO2: 50 – 150 €/ton
- H2: 2-6 €/kg

The CO2 price range is chosen based on the KEV [20], which assumes a range of 32-68 €/ton in 2030, and the Dutch CO2 tax for industry, which is expected to reach 127 €/ton in 2030 [21]. Analysis by CE Delft and TNO [12], based on multiple sources and several calculations shows hydrogen cost prices between 1 and 7 euro/kg in which the chosen sensitivity range fits.

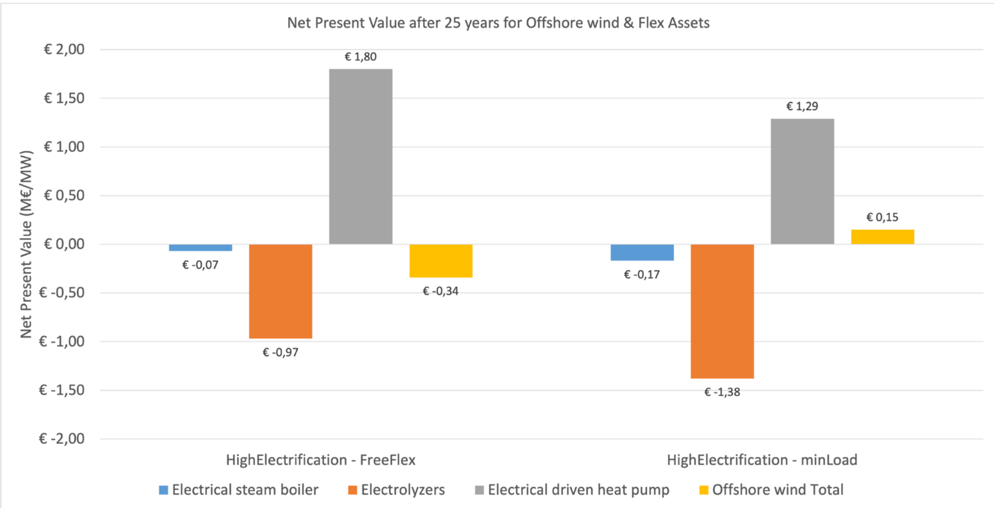


Figure 20. Net present value after 25 years for offshore wind & flex assets in S1 with FreeFlex & minLoad strategy.

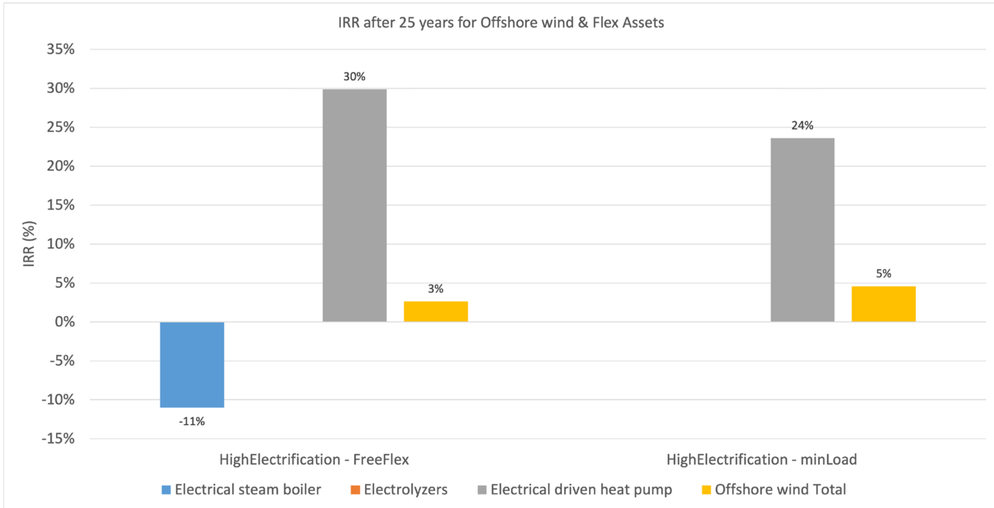


Figure 21. IRR after 25 years for offshore wind & flex assets in S1 with FreeFlex & minLoad strategy.

Figure 25 shows the IRR of the market based offshore wind business model for the High and Low Electrification scenarios for the sensitivity analysis.

- The business case of offshore wind is positively impacted by increased electrification, which makes the NPV positive under the assumptions of this analysis. Assuming a WACC of 4%, the business case of all CO2 and H2 price combinations are positive in the high electrification scenario. In the Low Electrifcation scenario, this is only the case for high CO2 prices.
- The business case of offshore wind is positively impacted by higher CO2 and H2 prices, which can make the NPV positive, even in the Low Electrification scenario. The impact of the CO2 price is greater than the impact of the H2 price, especially in the low electrification scenario. Only electrolysers depend on the H2 price, whereas most other assets depend on the CO2 price. Consequently, the CO2 price has a greater effect on the electricity price. In the low electrification scenario, there is almost no electrolyzer capacity, making the effect of the H2 price small.

Analysis on the integrated business models show that in the situation where the market based business model is not feasible, a PPA with Heat or Hydrogen improves the economic revenues to feasible levels. Furthermore, the PPA Hydrogen business model can also improve the business case of a feasible offshore wind farm. The energy carrier with which a PPA (Heat or Hydrogen) has the best economic value is determined by the CO2 and hydrogen price, as shown in Figure 26.

In the high electrification scenario, which is dominated by hydrogen, the results show that no PPA is the best solution at low H2 prices and a H2 PPA is the best result at high H2 prices. This follows the results from the baseline business model, which showed that the business case of offshore wind in this scenario benefits from the already installed flexible assets. Inducing a PPA will improve the IRR of offshore wind by 0-13%. The business case of offshore wind already was positive, which means that inducing a PPA will only increase profit, not make the investment profitable.

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 25. IRR of the market based offshore wind business model.

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 26. IRR of the best performing integrated business model, with the associated business model.

In the low electrification scenario, the market based model is not profitable due to a lack of flexibility assets. The PPA Heat is most profitable at low hydrogen prices. When the hydrogen prices increase, this will shift to PPA H2. The impact of the hydrogen price of this strategy is larger as the impact of the CO2 price. Inducing a PPA will improve the IRR of offshore wind by 5-33%, with the highest impact by a hydrogen PPA when there are high H2 prices. A PPA in this scenario will reduce the IRR of the flexible asset, which will have to be convinced by other values as economical. In this scenario a PPA construction is needed to make the NPV of the offshore wind positive. A PPA construction to make an offshore wind farm economical feasible will reduce the economic value of the flexible asset. The asset owners, mostly industry, will need to be compensated in other values in order to implement these solutions in practice. For instance, the asset owner can gain value through achieving recognition for using renewable energy or hedging of fluctuating electricity prices.

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