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Developing a long-lasting offshore wind business case towards a Dutch decarbonised energy system by 2050

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Abstract The integration of large-scale offshore wind power in the energy system will have a major effect on electricity markets. It may lead to large market price volatility due to the inherent variability of wind energy in terms of power fluctuations, forecast errors and insufficient flexibility on the demand side. This study models future business cases for offshore wind farms in two reference national scenarios for the Netherlands, namely NECP2030 and TRANSFORM. Results show that the value of offshore wind in 2030, according to NECP scenario is 39.9 €/MWh, and that electricity price in the TRANSFORM scenario, which considers aggressive development towards a sustainable economy, is a high 104 €/MWh by 2050. To consider ways of improving the return on investment for offshore wind farms in future markets, an optimisation problem is defined, where the wind farm has the choice to either sell the generated electricity to the spot market or to an electrolyser. Results show a potential advantage in using an electrolyser to produce green hydrogen for offshore wind farms, with net profit of 41.4 M€, compared to when offshore wind farms sell electricity solely to the spot market, where the profits are 36 M€.

1. Introduction & Literature

New obligations laid down in the first European Climate Law advocate for 55% net greenhouse gas (GHG) emission reductions by 2030 (compared to 1990 levels), on the way to European climate neutrality by 2050 [1]. The blueprint for this transformational change puts in place landmark strategies for offshore renewable energy. In particular, offshore wind energy in the European union is to increase from its current capacity of 12 GW to at least 60 GW by 2030 and to 300 GW by 2050. The Netherlands targets an offshore wind portfolio of at least 11.5 GW by 2030 with the vision of reaching 60 GW to 75 GW by 2050 in the Dutch North Sea [2].

Due to their inherent variability, the high share of electricity production from renewable energy sources (RES) increases stochasticity in the electricity market. This could lead to increased risk premiums and without subsidy support schemes, wind farm developers will be exposed to the price volatilities of electricity markets. This imposes increased risks of revenue losses, for instance due to unforeseen price drops, curtailments or inability to adapt to variations in the market and may also give rise to other market opportunities [3].

System integration, with conversion and storage technologies such as green hydrogen production, offers a promising prospect to develop long-lasting business cases for offshore wind farms (OWFs), while also increasing flexibility in the electricity market. However, it is still unclear how this can be achieved without endangering the stability of the network, the technical and economic considerations needed and the conditions that are profitable to OWFs in this integrated system. Energy and power system models, are widely used tools to evaluate future scenarios, yet the emergence of variable RES,



hybrid systems and new market mechanisms have required modellers to adapt both the methodology and the datasets used.

Regional cooperation to meet the flexibility challenge posed by high RES penetration in the EU is explored in [4]. An analysis of electricity interconnection potential to make use of synergies between the UK and France is seen in [5]. In Germany, to support the expansion of wind and solar power in the energy market, research into power to gas and power to liquid (P2X) technologies is recommended in [6]. A ten network development plan from the European network of transmission system operators (ENTSO-E) indicated that the cost and availability of flexibility providers such as P2X and batteries will influence investment decisions in RES [7]. Strategies to offset the cannibalisation effect of RES are explored in [8] and combining a RES investment with a flexible power supply contract (e.g. electrolysis) appeared to be a more effective hedging strategy. METIS, an energy modelling software, was used in [8], and can simulate the European energy system for electricity, gas and heat to high spatial and temporal granularity [9].

In comparison to the above literature, this study contributes in the following ways. This study quantifies the effects of integrating large amounts of RES, in particular offshore wind energy, into the Dutch electricity market and its impact on electricity prices. This is done with the use of a newly developed first order estimation tool which simulates the clearing mechanism of national wholesale electricity markets. The business case for upcoming OWFs in these future scenarios is investigated, as is the prospect of converting their energy into hydrogen. In particular, the techno-economic conditions needed for OWFs to obtain higher profits by either selling energy in the electricity market or to produce green hydrogen is looked into.

This paper first introduces the newly developed market modelling tool in section 2. This is followed by considering future scenarios and evaluating the future price of electricity and value of offshore wind energy in section 3. Section 4. describes a potential solution to improve the business case for OWFs with their integration to an electrolyser to produce green hydrogen. Section 5. discusses the conclusions and further work.

2. Methodology

The study models the Dutch electricity market in several scenarios with a special focus on the offshore wind development roadmap [10]. Offshore wind profiles are obtained based on the wind speed timeseries at the center coordinate of the wind farms in 2030. Based on the wind speed timeseries, an energy yield timeseries is obtained based on an interpolation from a sample 1 GW wind farm energy yield rose plot, calculated using TNO's internal wake loss estimation tool ECN Farm Flow [11].

2.1. Market model

The Dutch electricity market is modelled using the EYE (ElectricitY market price Evolution simulator) model [9]. The EYE model is an electricity system simulator which can analyze electricity prices given certain scenario inputs (such as energy asset specifications, commodity prices and expected demand). The EYE model is developed to model the future electricity grid and flexibility options with a first order estimation, in order to study complex system effects quickly.

2.1.1. Merit order: Using a merit order supply bid ladder, the model dispatches the cheapest available energy supply asset that is defined in each simulation step to cover the respective demand from the electricity system. The marginal cost of each supply asset is determined by the asset fuel price and its efficiency using the relation:

$$\text{Marginal cost} \left(\text{in } \frac{\text{€}}{\text{MWh}} \right) = \text{Fuel price} \left(\text{in } \frac{\text{€}}{\text{MWh}} \right) + \text{CO}_2 \text{ cost} \left(\text{in } \frac{\text{€}}{\text{MWh}} \right) \quad (1)$$

2.1.2. Flexible demand: Besides must-run electricity demand, an advantage of the model is the possibility to simulate flexible assets (such as batteries, electrolyzers, hybrid boilers and industrial heat pumps) which represents the future of electricity market demand. These assets have a number of

characteristics which could be set for each simulation (e.g. bidding strategies, forecast window lengths, round trip costs, relevant efficiencies, nominal capacities etc.).

2.1.3. Price clearing: The price clearing is done by finding the intersection of the supply and demand bid ladders. By providing as inputs the characteristics of electricity supply assets (e.g. wind, solar, natural gas and coal), fuel prices, CO₂ taxation, renewable asset production profiles, electricity demand and flexibility assets, the model derives a market clearing price on an hourly basis, thus simulating future spot market prices. With output market clearing prices, the annual value of offshore wind is estimated by the equation below:

$$\text{Value of offshore wind (in €/MWh)} = \sum_{i=1}^{8760} (p_i * c_i) / \sum_{i=1}^{8760} (p_i) \quad (2)$$

where p_i is the electricity sold from all offshore wind assets and c_i is the resulting market clearing price at each simulation timestep.

3. Scenarios to evaluate future value of OWFs

Offshore wind energy development has traditionally been driven by government support schemes. Recent projects however have tended to move towards becoming subsidy free, and it is therefore a challenge for wind farm developers to ensure good returns on investment. To investigate the future business cases for OWFs, two reference national scenarios are modelled namely NECP2030, based on the Dutch Integrated National Energy and Climate Plan (NECP) [2], and TRANSFORM where the Dutch society opts for aggressive structural changes towards a sustainable economy [12].

3.1. Modelling set up

Existing Energy System Models (ESM) are configured and set up to model the above scenarios. First, the OPERA ESM [13] is run under the NECP and TRANSFORM scenarios for 2030 and 2050 and its outputs (such as the hourly time series of demand for electricity and flexibility, the imports and exports) are used in the EYE model to obtain future prices in the Dutch electricity market. Additionally, the outputs of the future electricity prices from the EYE model are compared with results of COMPETES ESM [14] to have a robust understanding of trends of future prices in the electricity markets.

3.2. NECP2030

The installed capacity of offshore wind in 2030 will be 11.5 GW, and the Dutch electricity demand will be 137 TWh, not including flexible assets.

Table 1. Select inputs for NECP2030

Parameter	Value
Electricity demand	137 TWh
Flexible assets demand	30 TWh
PV capacity	20 GW
Onshore wind capacity	6.9 GW
Offshore wind capacity	11.5 GW
Natural gas capacity	17.8 GWh

From the price duration curve in Figure 1, the value of offshore wind in 2030 is 39.9 €/MWh. Consequently, the levelized cost of energy (LCoE) of OWFs must therefore be lower than this value to ensure a positive business case for wind farm owners.

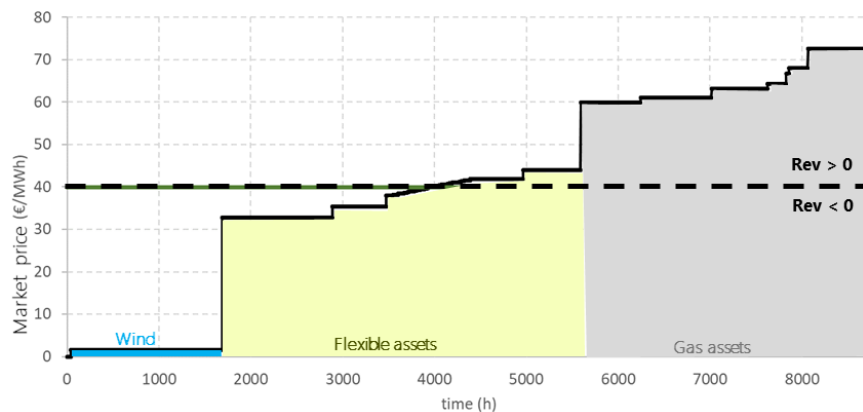


Figure 1. Market price duration curve for baseline NECP2030

Figure 1 shows that non-renewable assets will set the highest electricity prices in 2030. Also, flexible assets are the largest temporal price setters in the electricity market. The influence of flexible assets is further solidified by either removing them or doubling their capacity in two sensitivities. Table 2 shows that the value and utilisation of offshore wind decreases substantially without flexible assets, highlighting their importance.

Table 2. Influence of flexible assets on offshore wind value

Sensitivity	Value of offshore wind (€/MWh)	Offshore wind utilisation
Baseline flexible assets	39.9	100%
Remove flexible assets	23.5	55%
Double flexible assets	51.1	100%

3.3. TRANSFORM

This scenario envisions a society with radical behaviour and infrastructural changes towards a sustainable economy where electricity from solar and wind energy will become attractive for functions ranging from heating, mobility and industrial processes. Consequently, there is a substantial increase in both the electricity and flexible demand by 2050. The duration curves are characterized by higher prices, with an average of 51 €/MWh for 2030 and an extremely high price of 104 €/MWh in 2050. Figure 2 shows the market price duration curves of TRANSFORM 2030 and 2050 scenarios.

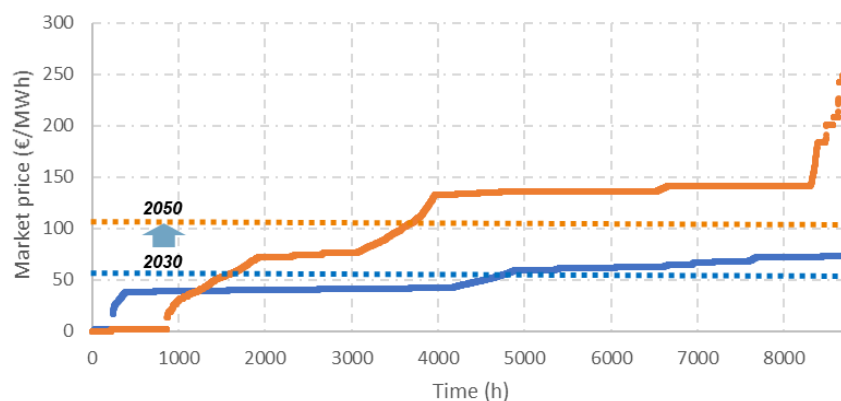


Figure 2. Market price duration curve for TRANSFORM 2030 and 2050.

4. Optimising the business case of OWFs

To improve upon the future value of offshore wind energy an example optimisation problem is defined. A reference 700 MW offshore wind farm is modelled with an electrolyser of the same capacity which

under different scenarios uses profit maximization as the optimization objective. Table 3 lists inputs of the optimisation problem.

Table 3. Setup of offshore wind business case optimisation problem

Parameter	Value
Simulation length	3 months
Offshore wind asset capacity	700 MW
Offshore wind factor	48%
Maximum capacity electrolyzer	10 ton H ₂ /h (1:1 wind-electrolyzer ratio)
Conversion factor electrolyzer	65 MWh/ton H ₂
Min. continuous operation electrolyzer	10% of capacity

4.1. Objective function

The objective function is to maximize the OWFs profit. The OWF has the choice of either selling wind energy to the spot market or to an electrolyser. It is optimized on an hourly basis and the profit is maximized over simulation length. The optimization problem is based on the model and equations developed in [15], a study on the wind portfolio of the Spanish electricity market.

$$OWF \text{ profit} = \sum_{h=1}^{h=8760} [(Revenues - Costs)_{day \text{ ahead } h} + (Revenues - Costs)_{hydrogen \ h}] \quad (3)$$

In Figure 3, solid lines represent the flow of electricity (or chemicals) whereas dashed lines represent the flow of money. Green and red arrows indicate the revenues and the costs from the wind farm's perspective. W is the wind energy generation, DA is the day-ahead market, E_{da} is the energy bought from the electricity market to supply minimum requirements of energy to electrolyser when W is not enough and P is the price.

The revenues and costs for the offshore wind farm are:

$$Revenues \text{ wind}_{da, h} = W_{da, h} * P_{da, h} \quad (4)$$

$$Costs \text{ wind}_{day \text{ ahead}, h} = W_{da, h} * LCOE_h \quad (5)$$

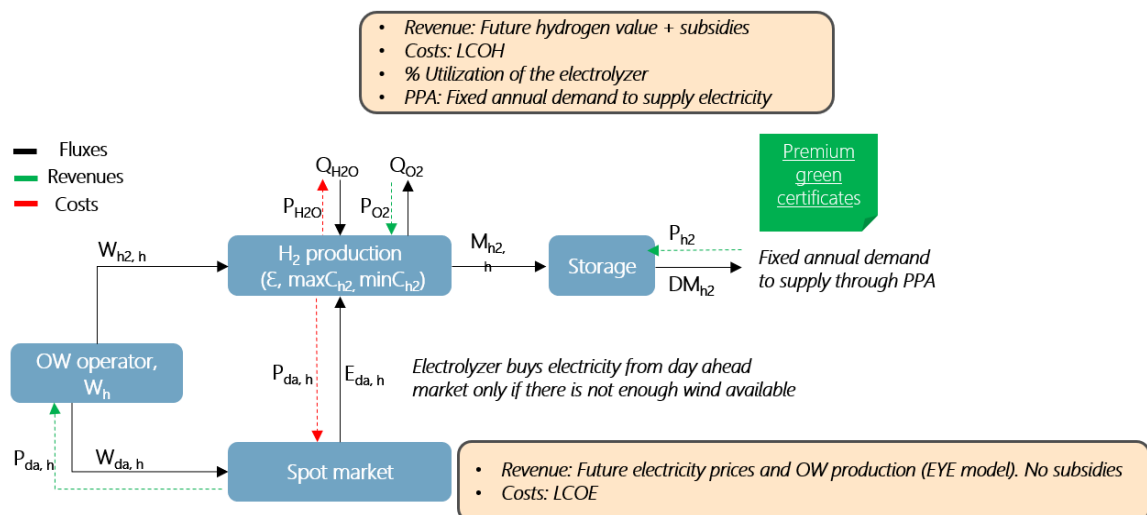


Figure 3. Flow diagram of the power-to-hydrogen business model combining the offshore wind energy generation and electrolysis.

4.2. Constraints

Profit for the OWF is obtained by either selling the wind energy in the electricity market or producing green hydrogen which is sold to third parties annually. A fixed annual supply of green hydrogen demand is modelled and the electrolyser is modelled at a minimum continuous load to avoid start-up times with

a minimum utilization of 10%. Investment costs, capital expenditure and operational expenditure of the integrated model are analysed and taken into account as Levelized cost of Electricity (LCoE), when selling the wind energy in the electricity market and Levelized cost of Hydrogen (LCoH), when selling into the hydrogen market. In addition to the parameters in Table 3, for this case study, the cost of producing wind energy (LCoE) and cost of producing hydrogen (LCoH) are assumed to be 40 €/MWh and 3 €/kg_{H2} respectively. The constraints of the offshore wind energy generation, electricity market and green hydrogen production considered are:

$$W_{da,h} + W_{H2,h} = W \quad (6)$$

$$E_{da,h} + W_{H2,h} \leq \text{Max capacity electrolyser (Max cap)} \quad (7)$$

$$E_{da,h} + W_{H2,h} \geq \text{Minimum electrolyser continuous load (Min load)} \quad (8)$$

$$\text{Annual } DM_{H2} \geq \text{Annual required green hydrogen demand to supply} \quad (9)$$

4.3. Results and discussion

With the above optimisation setup, three cases are modelled as described in Table 4.

Table 4. Optimisation cases and results

Cases	Description	Offshore wind profits (M€)	Electrolyser capacity (tonH2/h)	Electrolyser utilisation
Case A	All OW energy to spot market	36.0	N/A	N/A
Case B	Optimise selling b/w spot market and electrolyser	41.4	10	18%
Case C	Downscale electrolyser capacity	39.6	3	35%

Selling all the energy in the spot market (Case A) results in a profit of 36.01 M€ for the OWF. When the OWF chooses to either sell to the spot market or to the electrolyzer (Case B), the profit increases to 41.4 M€. In Case B, the electrolyser has a capacity of 700 MW and is capable of producing 10 ton of hydrogen per hour. However the electrolyzer utilization is only 18% and to optimize this, its size is reduced by a factor of three. Table 4 shows an increase in electrolyzer utilization to 35%, but with reduced profits.

A further sensitivity analysis is performed, where the LCoE and LCoH are varied to see their influence on the electrolyser utilisation (Figure 4 left). The utilisation increases with low LCoH, this effect is justified as the more the electrolyser is used, the more the fixed investment costs are covered by the hydrogen production. Also, the LCoE seems to be indirectly proportional to the electrolyser utilization rate, meaning that when the LCoE is low the system prefers to sell the electricity to the spot market instead of feeding it to the electrolyser. Conversely, when the LCoE is high, the electrolyser is preferred, increasing its utilization. This is because the system looks at alternative ways to improve the value of offshore wind energy rather than selling it to the spot market.

Finally, the influence of this sensitivity on the offshore wind profit is seen in Figure 4 (right). The highest profit, 49.9 M€, is naturally obtained at the lowest operating costs of wind and electrolyser. The limit from which the profit starts to be positive is highlighted by the grey layer. Furthermore, from this figure it is clear that the variation of LCoE is more pronounced on the profits than the variation of LCoH.

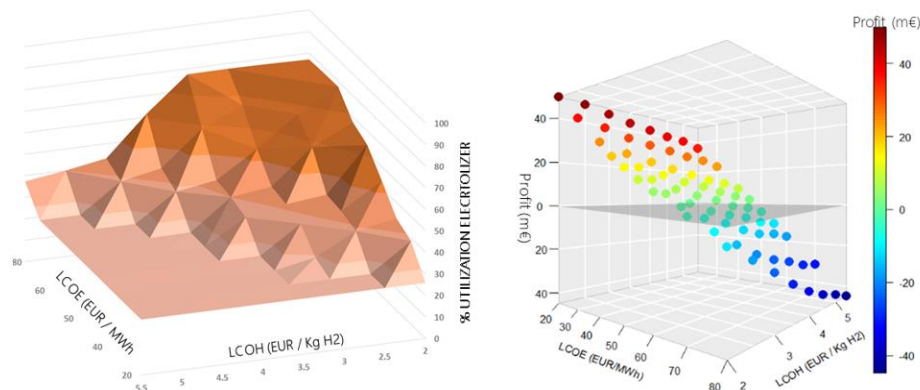


Figure 4. Electrolyzer utilization (%) depending on LCoE and LCoH (left). Optimization OWF profits results depending on LCoE and LCoH (right)

5. Conclusions and further work

In this work, the integration of high capacities of RES into the electricity market is explored. Results show that based on two national scenarios modelled in this study for 2030 and 2050, there will be a need for higher amounts of flexible assets such as batteries and electrolyzers to support the business case for RES. Greater use of flexible assets will in turn increase electricity prices, with similar trends on future electricity prices observable in several European level studies of neighbouring countries.

Next, with the objective of maximising profits for a 700 MW wind farm, an optimisation problem is defined, where the wind farm has the choice to either sell electricity directly to spot market, or to an electrolyser. Results show that there is an increase in profit for the OWF when its energy is converted into hydrogen rather than being sold on the spot market.

A follow up for this study would be to model in greater detail the interaction between energy generation assets and flexible assets. In current energy system models, including the EYE model, it is possible to separately model various types of current energy generation and flexible assets. However, in the future energy system, hybrid or compound systems which can place bids on the electricity market as a single asset may be necessary. The business case for compound assets as well as their influence on setting the future prices of electricity will be explored in subsequent studies.

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