North Sea Energy
offshore system integration

D3.4 WHITE PAPER

North Sea Energy 2023-2025

Offshore Energy System Value and Business Cases: Aligning Project Decisions with Societal Objectives

North Sea Energy offshore system integration

D3.4 WHITE PAPER

North Sea Energy 2023-2025

Offshore Energy System Value and Business Cases: Aligning Project Decisions with Societal Objectives

Prepared by:

NEC
Rob van Zoelen
Salar Mahfoozi

TNO
Sander Blom
Iratxe Gonzalez Aparicio

Checked by:

TNO
Joris Koornneef

Zero 50
Sjoerd Meijer

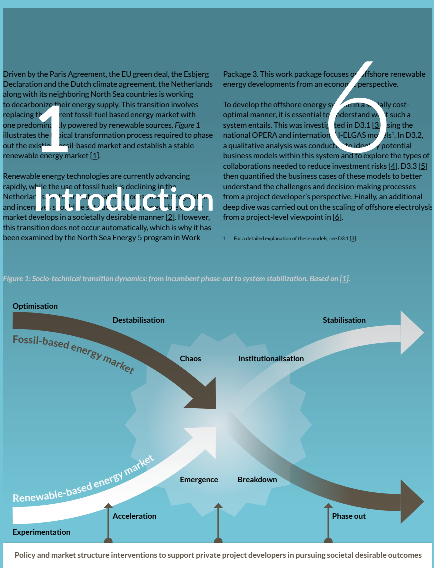
Approved by:

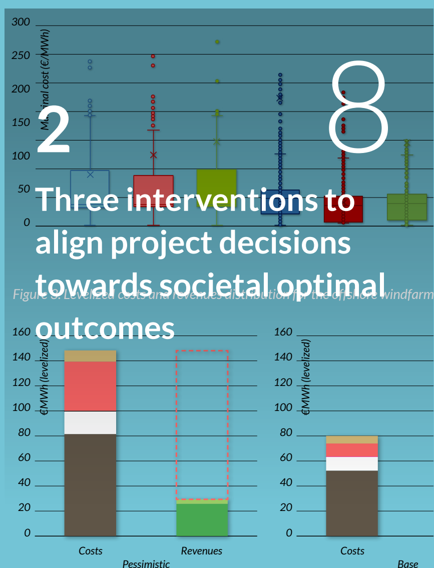
TNO
Madelaine Halter

The project has been carried out with a subsidy from the Dutch Ministry of Economic Affairs and Climate, National Schemes EZK-subsidies, Top Sector Energy, as taken care of by RVO (Rijksdienst voor Ondernemend Nederland)

Contents

1. Introduction	6
2. Three interventions to align project decisions towards societal optimal outcomes	8
2.1 Market conditions and financial viability of offshore wind	8
2.2 Deployment of onshore and offshore electrolysis	10
2.3 Electricity grid connection costs and utilization	14
3. Conclusions	18





2. Introduction

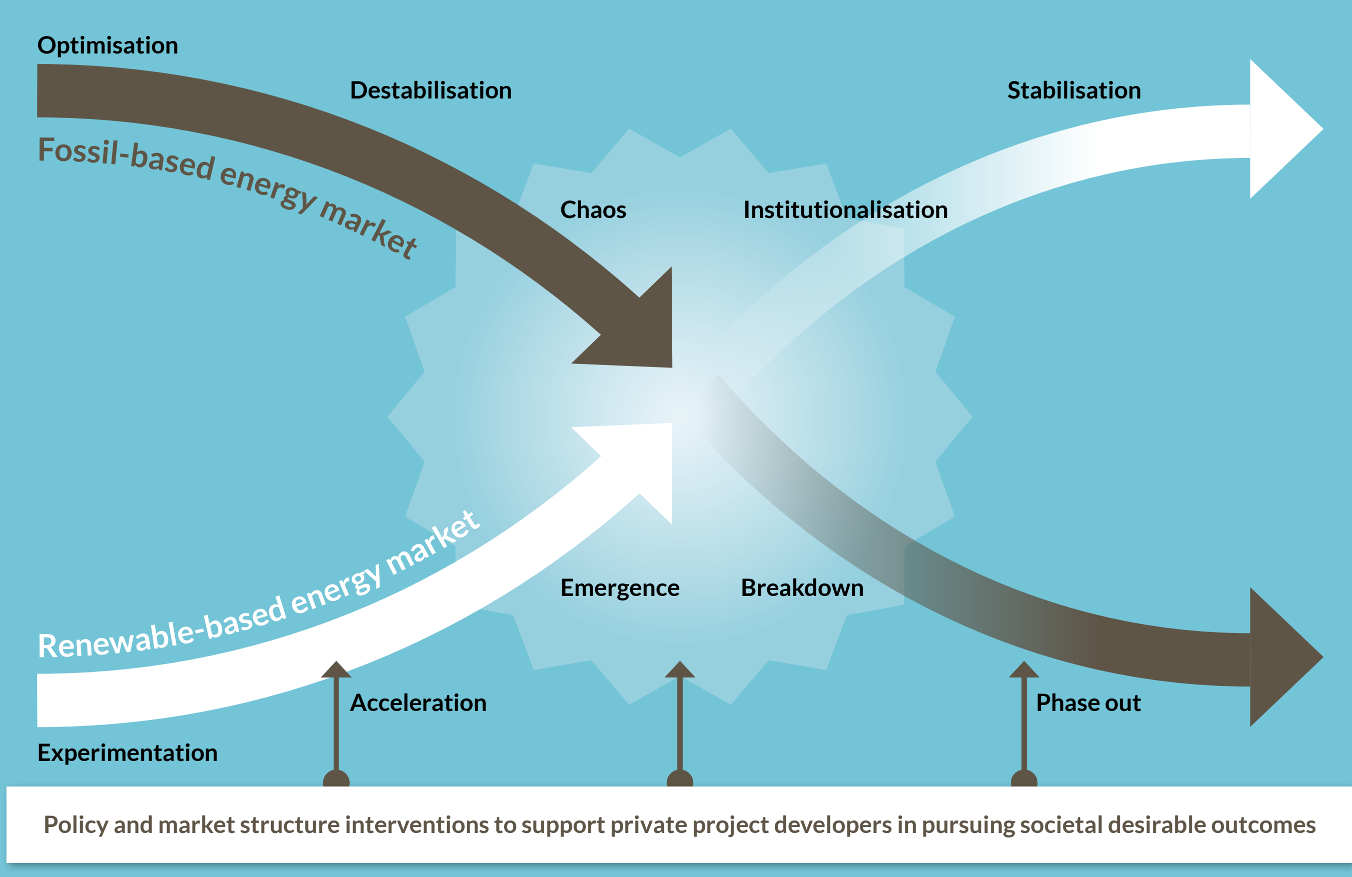
Driven by the Paris Agreement, the EU green deal, the Esbjerg Declaration and the Dutch climate agreement, the Netherlands along with its neighboring North Sea countries is working to decarbonize their energy supply. This transition involves replacing the current fossil-fuel based energy market with one predominantly powered by renewable sources. *Figure 1* illustrates the typical transformation process required to phase out the existing fossil-based market and establish a stable renewable energy market [1].

Renewable energy technologies are currently advancing rapidly, while the use of fossil fuels is declining in the Netherlands. In this transformation process market regulation and incentives should be set such that the renewable energy market develops in a societally desirable manner [2]. However, this transition does not occur automatically, which is why it has been examined by the North Sea Energy 5 program in Work Package 3. This work package focuses on offshore renewable energy developments from an economic perspective.

To develop the offshore energy system in a socially cost-optimal manner, it is essential to understand what such a system entails. This was investigated in D3.1 [3] using the national OPERA and international I-ELGAS models[1]. In D3.2, a qualitative analysis was conducted to identify potential business models within this system and to explore the types of collaborations needed to reduce investment risks [4]. D3.3 [5] then quantified the business cases of these models to better understand the challenges and decision-making processes from a project developer's perspective. Finally, an additional deep dive was carried out on the scaling of offshore electrolysis from a project-level viewpoint in [6].

1 For a detailed explanation of these models, see D3.1 [3].

Figure 1: Socio-technical transition dynamics: from incumbent phase-out to system stabilization. Based on [1].



During the research underlying these extensive reports, it was found that within the current market regulatory framework, project developers are not always effectively incentivized to make decisions that align with societally optimal outcomes. As a result, a gap can emerge between system value and business value. The aim of this white paper is to provide the main insights on the misalignment between system and project developer value across three key themes, and furthermore, to provide suggestions for interventions that incentivize project decisions towards societal optimal outcomes.

This is achieved by addressing three key themes where system value and project developer value are not yet aligned:

1. The market conditions and financial viability of offshore wind;
2. The deployment of onshore and offshore electrolysis;
3. The costs and utilization of electricity grid connections.

In Chapter 2, each theme is explored by explaining the discrepancies between system value and project developer value, along with suggestions for how these can be better aligned.

Market regulation and incentives should be set such that the renewable energy market develops in a societally desirable manner

3. Three interventions to align project decisions towards societal optimal outcomes

The key differences between the system perspective and the project developer perspective across the three themes are summarized in Table 1. The following chapter provides a more detailed analysis of these differences and offers recommendations for interventions to better align project decisions with socially optimal outcomes.

3.1 Market conditions and financial viability of offshore wind

The first point of pressure arises from the need for high levels of offshore wind to achieve cost-optimal decarbonization in the Netherlands. However, as more offshore wind capacity is deployed in the system, the risk of electricity price cannibalization increases which negatively impacts the economic viability of the offshore wind business case.

3.1.1 Societal cost perspective

In many future energy scenarios offshore wind is projected to become the primary source of energy for the Netherlands [7] [8]. In line with this, the energy system optimization run with the OPERA model for deliverable D3.1 [3], consistently selected significant large offshore-wind capacities under all scenario assumptions. The cost-optimal model deployed offshore wind capacities ranged from 12-15 GW in 2030, to 28-45 GW in 2040, ending in a range of 40-70 GW by 2050. Given the current forecast of cost developments, it outcompetes solar PV and nuclear energy from a societal cost perspective and is less limited by spatial and societal acceptance constraints than onshore wind.

In a marginal cost-based market, such a large share of (one source of) variable renewable energy will lead to many hours of low or even negative prices. This effect is clearly visible in the marginal cost curves as a result of the market modelling, shown in *Figure 2*. In 2030, the price is still set by gas-based production for many hours, whereas in 2050 prices are set by variable renewable energy, directly or indirectly.

It needs to be mentioned that in our approach flexible types of electricity demand are included in the national OPERA system optimization, but when modelling the market dynamics of such

Table 1: Key Misalignments between System and Project Developer Perspectives.

Theme	System / societal perspective	Project developer perspective
Market conditions and financial viability of offshore wind	High levels of offshore wind for cost-optimal decarbonization and low energy prices.	Cannibalization of electricity prices hinders OWF business case.
Development of onshore and offshore electrolysis	Partial offshore electrolysis lowers societal costs and onshore spatial pressure.	Projections suggest that onshore electrolysis is likely to retain a cost advantage over offshore platform-based electrolysis from a project developer perspective.
Electricity grid connection costs and utilization	Connecting wind farms and electrolyzers with smaller (undersized) electricity cables can lower system costs.	OWF developer maximizes grid capacity since it is not burdened with the costs, and it minimizes electricity curtailment
	Providing at least some grid connection to offshore electrolyzers (instead of fully off-grid) is more cost-effective due to high value of electricity in hours of low generation	Offshore electrolysis business case minimizes grid connection due to significant impact of tariffs.

Table 2: Summary of theme 1 – Market conditions and financial viability of offshore wind

Theme	System / societal perspective	Project developer perspective
Market conditions and financial viability of offshore wind	High levels of offshore wind for cost-optimal decarbonization and low energy prices	Cannibalization of electricity prices hinders offshore windfarm business case
Key conclusions and recommendations	• Consider a fallback support option for offshore wind; • Consider supply-demand matchmaking mechanisms in future tenders for offshore wind and electrolysis; • Investigate structural measures to realize all required individual business cases in high renewable energy scenarios; • Research the exact policy mix to harmonize supply-demand development of offshore wind and electrolysis.	

a system via the international I-ELGAS model only flexible demand of electrolysis is endogenously modelled, leading to an underestimation of the marginal costs during the moments that the offshore wind farms are generating electricity. Either way, the large deployment of offshore wind results in low marginal electricity costs which can be beneficial for society, but they form a significant investment risk for offshore wind farm project developers.

3.1.2 Project developer perspective

In D3.3 [5] marginal cost curves of electricity resulting from the I-ELGAS modelling were taken as electricity prices in order to calculate the revenues of the offshore windfarm business case. It was seen that the relatively low capture prices of 28-36 €/MWh by 2030 and 10-25 €/MWh by 2050 were significantly lower than the levelized cost of offshore wind, which were seen to be 80 €/MWh for projects that start operation by 2030 (See *Figure 3*).

Future electricity prices are highly uncertain, and therefore it is not possible to make predictions on the future feasibility of offshore wind project business cases. However, the results show that if high offshore wind and other renewable capacities are deployed, there is a significant risk for price cannibalization.

Figure 2: Hourly electricity marginal costs for three energy scenarios simulated in the I-ELGAS market model, for years 2030, 2040 and 2050 [3].

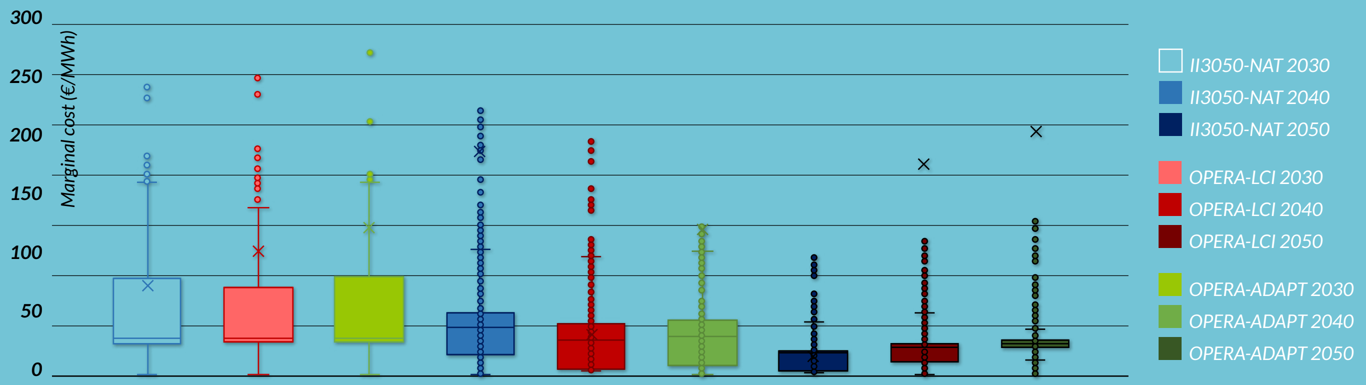
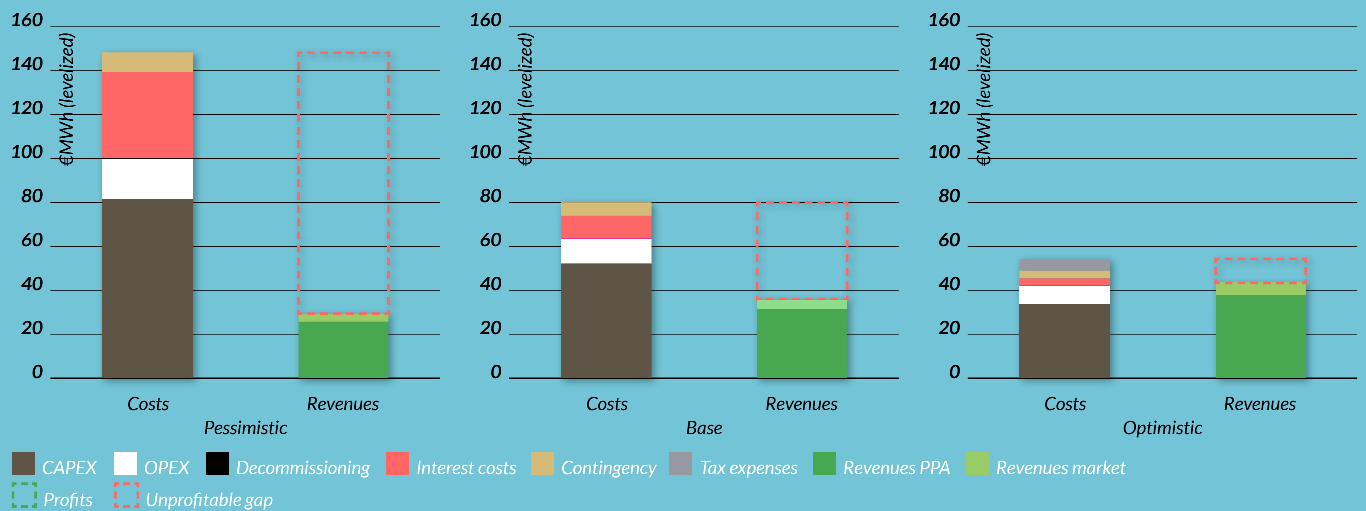


Figure 3: Levelized costs and revenues distribution for the offshore windfarm business case [5].



This occurs because offshore windfarms depend on the wind conditions for their generation profile. If there is a lot of wind, windfarms in the system start generating electricity and when the demand for electricity does not equally rise, the price of electricity is likely to drop during those moments. The potential of such future price cannibalization is already enough to create risks that could hamper future investment attractiveness in offshore wind. Hence, solutions need to be found to maintain a stable investment climate in order to deploy the system optimal levels of offshore wind.

3.1.3 Conclusion and recommendations

Offshore wind plays a substantial role in all societal cost-optimal scenarios that were analyzed. However, deploying such significant capacities of offshore wind could lead to a significant risk of price cannibalization that could hamper its required investments and return from investments for developers and project financers. The following interventions are required to enable significant deployment of offshore wind in the Dutch energy system without electricity price cannibalization effects.

To support the continued stable development of offshore wind, a harmonized stimulation of (flexible) electricity demand is necessary. However, the current level of government influence in stimulating electricity demand remains limited. Such stimulation could involve, but is not limited to, measures like power-to-heat technologies, industrial demand response, energy storage solutions such as batteries, and electrolysers. It is essential to align the timelines of tenders and support schemes for these technologies and corresponding energy demand to ensure effective system integration.

Therefore, the following recommendations are considered of high importance:

- A fallback support option, such as a minimum price guarantee or contract for difference, for offshore wind could be considered;
- Consider options for future supply-demand matchmaking in offshore wind and electrolysis tenders, such as a domestic H2Global-like mechanism[2] in which (electricity and hydrogen) supply and demand side auctions are held next to each other and the price differences are minimized by an intermediary backed-up by the government;
- A detailed analysis is needed to investigate if there are future high renewable scenarios in which all the required individual business cases (e.g. offshore wind, electrolysers, energy storage, back-up generation) become economically feasible on the long term. And if this turns out to be not possible, provide suggestions on what structural measures should be taken to realize a renewable energy system with the lowest societal costs;
- Further research is needed to determine the optimal policy mix and operational strategies for aligning the supply from offshore wind farms with the demand from electrolysers. This includes both the installation timeline (e.g. synchronized capacity roll-outs) and dispatch strategies (e.g. when and how electrolysers operate), considering the potentially different behavior of onshore versus offshore electrolysis in respsonse to offshore wind generation profiles.

3.2 Deployment of onshore and offshore electrolysis

The second misalignment concerns the deployment of onshore versus offshore electrolysis. From a societal perspective, partially deploying offshore electrolysis can help reduce electricity infrastructure costs, curtailment due to avoided onshore congestion, onshore spatial pressure, and overall energy prices [3]. However, for project developers, offshore platform-based electrolysis currently involves higher costs and greater risks than onshore electrolysis, with no substantial incentives or support mechanisms in place to offset these challenges.

2 For more information about this mechanism see the H2Global website.

Table 3: Summary of theme 2 – Deployment of onshore and offshore electrolysis

Theme	System / societal perspective	Project developer perspective
Deployment of onshore and offshore electrolysis	Partial offshore electrolysis lowers societal costs and onshore space	Deploying onshore electrolysis is more profitable for project developers than offshore electrolysis
Key conclusions and recommendations	• Differentiation in support between onshore and offshore electrolysis is needed to develop them both; • Electrolyzers (onshore and offshore) should be incentivized and rewarded for contributing to avoidance of electricity grid expansions; • Significant effort from industry, government and research institutes is needed to decrease (offshore) electrolysis CAPEX and OPEX.	

3.2.1 Societal perspective

Offshore hydrogen production is a robust solution of the energy system cost-optimization for all investigated scenarios, indicating that offshore hydrogen results in lower costs from a societal perspective. The benefits are small, however, ranging from 30 – 350 million euros annually in 2050 for the base scenarios. This benefit is much lower than calculated in earlier studies [9] [10], with the most important reason being the higher assumed cost for electrolysis in this study, including the cost factor for going offshore. A decomposition of the avoided costs due to offshore electrolysis in scenario TRANSFORM 2050 is shown in *Figure 4*.

So the additional costs of building electrolyzers offshore are outweighed by the significant costs savings in offshore electrical infrastructure, but the difference is small and cost developments of offshore hydrogen versus the offshore electricity chains are very uncertain. Thus no strong conclusion can be made from the societal cost perspective alone.

However, additional societal benefits of offshore hydrogen production were shown in D3.1 [3]. A relative increase of electrolyzer dispatch of up to 43% was found when comparing the 2050 energy system with offshore hydrogen to one without, in the market modelling approach. Additionally, a decrease of electricity and hydrogen prices of up to 22% and 30% respectively, and a curtailment decrease of up to 48 TWh was found. These effects are mostly driven by (avoided) congestion in the onshore electricity network. To give a sense of scale, 48 TWh corresponds to roughly 40% of the Netherlands current total annual electricity demand (110-120 TWh/year [11]). Additionally, a significant amount of space can be saved onshore, ranging from 140 – 480 hectares in 2050.

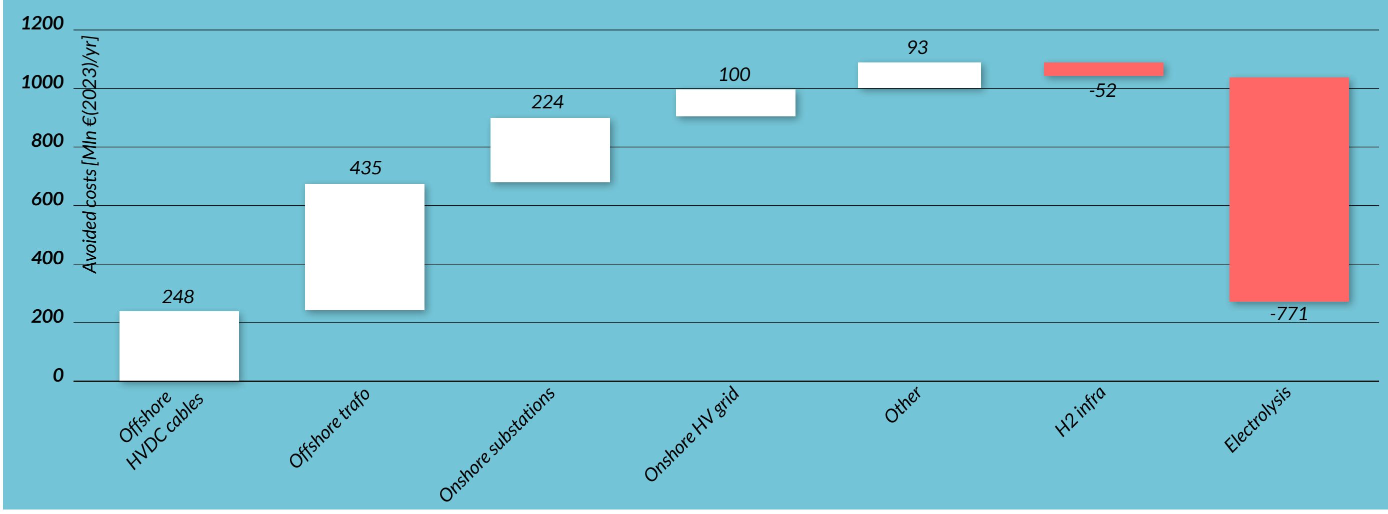
It is important to note that the modeled system costs of offshore electrolysis include assumptions on hydrogen transport to shore based on pipeline transportation. While alternative modes like ship-based transfer (e.g. LOHC or ammonia) were not explicitly modeled, the pipeline-based cost assumptions aim to capture the dominant transport configuration envisioned in current Dutch and North Sea policy roadmaps.

3.2.2 Project developer perspective

Despite the potential system value of offshore electrolysis, the business case of such a project is very economically challenging. Projected levelized costs are 310 €/MWh, or: 10.3 €/kg (with uncertainty range between €205 and €570/MWh, or 6.8 and 19 €/kg) by 2040, driven primarily by high electrolyzer CAPEX, the costs of electricity, stack replacements and potential electricity grid connection costs. The hydrogen revenues resulting from dispatch modelling based on the infrastructure operator scenarios were just in the range of 60-66 €/MWh (or: about 2-2.2 €/kg). If significant revenues of 5 €/kg for Hernieuwbare Waterstofeenheid Industrie (HWI[3]) would be gained as part of the hydrogen offtake mandate, the cost gap becomes smaller. However, the future HWI price is highly uncertain, and a 5 €/kg price would imply significant

3 HWI refers to hydrogen guarantees of origin

Figure 4: Decomposition of avoided system costs by 2050 by performing offshore electrolysis [3].



additional costs for hydrogen consumers, which typically manufacture products that need to be competitive on a global market.

Onshore electrolysis faces similar challenges; however, even for a smaller scale system (100MW instead of 500MW) the levelized cost of hydrogen (LCOH) is significantly lower than those of offshore electrolysis (approximately €250/MWh) while the potential revenues stay the same. There is a potential cost disadvantage for onshore electrolysis if the 100MW onshore electrolyser needs a full electricity grid capacity to receive enough electricity, while the offshore electrolyser can directly connect to an offshore windfarm. In *Figure 5*, this is shown by assuming a 100MW electricity grid connection for the onshore electrolyser and a 200 MW grid connection for the 500MW offshore electrolyser.

As a result of the lower CAPEX and OPEX of onshore electrolysis compared to offshore electrolysis, investing in onshore electrolysis involves lower risk and offers higher potential returns compared to offshore platform-based electrolysis. Without targeted measures or support, offshore electrolysis is at risk of becoming stranded in the so-called "valley of death". It should be noted that detailed business case assessment for other offshore electrolysis configurations, such as in-turbine, near-turbine and island based offshore electrolysis have not been assessed within this phase of the North Sea Energy program.

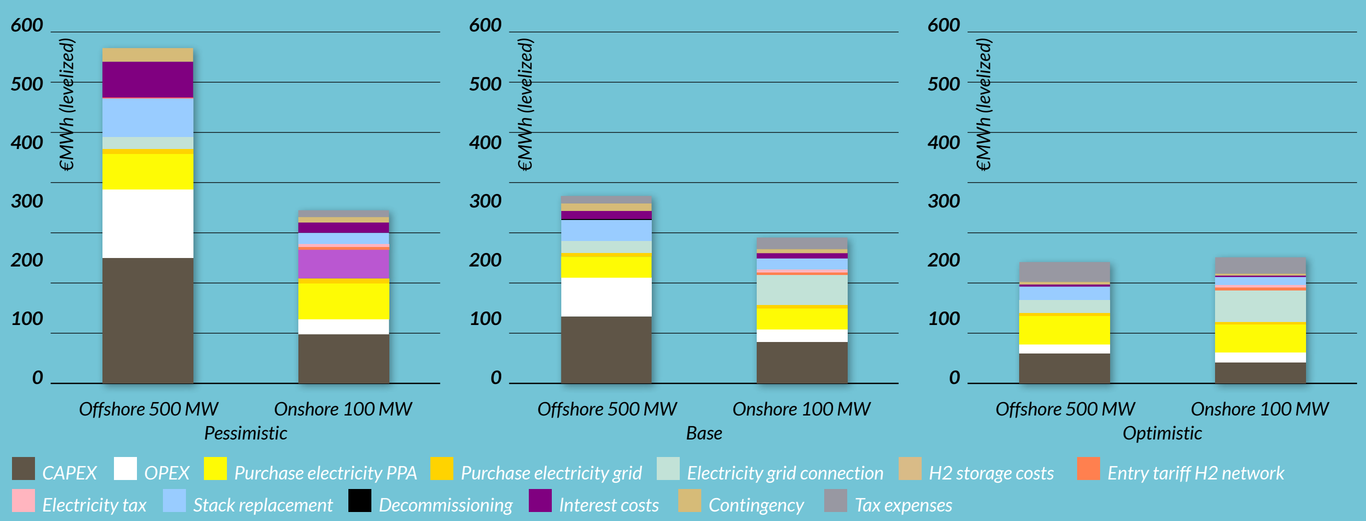
3.2.3 Conclusions and recommendations

Due to updated cost assumptions, the projected system cost benefits of offshore electrolysis are now less substantial than previously estimated a few years ago [7] [8]. Nevertheless, there are still quantifiable societal benefits and additional advantages that justify supporting offshore electrolysis through the "valley of death". Ultimately, this is a decision for policy makers. If deployment of offshore electrolysis is deemed politically desirable, the following recommendations should be considered:

- Differentiated support mechanisms for onshore and offshore electrolysis will be necessary to ensure the development of both. Without such differentiation, onshore electrolysis will likely outperform offshore electrolysis based solely on business case viability.
- Electrolysers should be incentivised for contributing to the avoidance of of onshore/offshore electricity grid reinforcements, curtailment reduction and net conegstion particularly when strategically located offshore, as this can lead to significant system cost reductions.
- It is evident that the future offshore wind industry needs flexible electricity consumers. Electrolysers, despite its high costs, remain an essential part of the solution. The offshore and hydrogen industry should, more than ever, work together on realising cost reductions, proof-of-concept and innovations to scale up the required technologies. This involves:

to be continued on page 14

Figure 5: Project level comparison of platform-based offshore electrolysis and onshore electrolysis levelized costs [5].



Textbox 1: Sizing considerations for the deployment of offshore electrolysis projects.

For the DEMO-II project at Ten Noorden van de Wadden wind area, a 500 MW offshore electrolysis demonstration is currently being considered in combination with a 700 MW offshore windfarm. Reducing the size of the electrolyser can increase its full load hours, thereby improving the overall business case. For example, in an off-grid configuration with a 100 MW electrolyser, the utilization increases to 96%, compared to the 65% with a 500 MW electrolyser. The hydrogen price at which the business case becomes positive is approximately 5.5 €/kg. Reducing the ratio between the wind capacity and electrolyser size reduces the required hydrogen price, narrowing the business case gap by around 2 €/kg of green hydrogen. For more information see [6].

Given the significant cost gap and support intensity of the first offshore electrolysis project(s), a consideration could be to size the electrolysers relatively small to the offshore wind farm in this initial phase. It should be noted that the assumed priority of the offshore wind farm to supply electricity to such a small electrolyser might not be the natural preference of the wind farm project developer. However, for the sake of offshore electrolysis development, it might be considered to include this requirement in the tendering criteria for this demo project. As the current analysis does not take into account the impact of the electricity capture prices associated with such oversized configurations, future research should explore the optimal offshore windfarm-to-electrolyser ratio from a project developer's across different decades.

Table 3: Summary of theme 2 – Deployment of onshore and offshore electrolysis

Variables	500 MW	100 MW
Elec. utilization	65%	96%
CAPEX (4000€/KW capacity elect.)	*200m€/y*	*40m€/y*
H2 produced yearly	*62,7M kg*	*18,5M kg*
OPEX	*€60M/year*	*€12M/year*

For future offshore electrolysis deployment from a system perspective, cost-optimal ratios between offshore wind and offshore electrolysis capacity for different regions are presented in Figure 7. In general, the ratio becomes higher towards 2050 and in areas located further from shore. As increasingly large offshore wind deployment expands into more remote northern zones, it becomes more cost-effective to deploy a larger share of hydrogen production alongside offshore wind development. The ratio ranges from 20% to 50% for most simulation outcomes, with a maximum of 57% determined by the value of electricity in lower wind hours. From a system perspective, electricity is prioritized for direct use during low generation hours, while hydrogen production is favored during surplus generation. Therefore, the relative value of additional electrolysis capacity decreases as the ratio of electrolysis to wind capacity increases.

Figure 6: Break-even point on the electrolyser size versus green H_2 price for a positive business case [6].

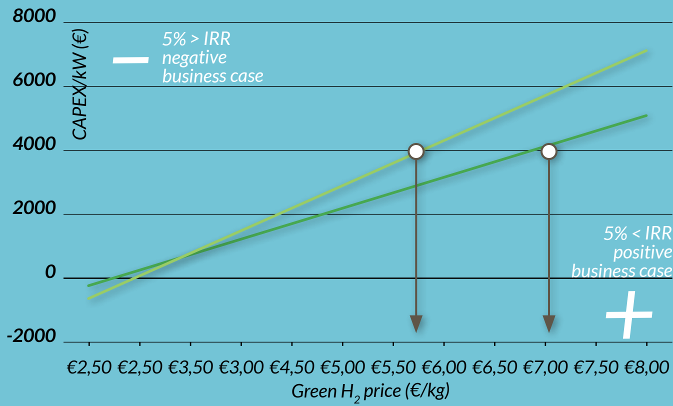
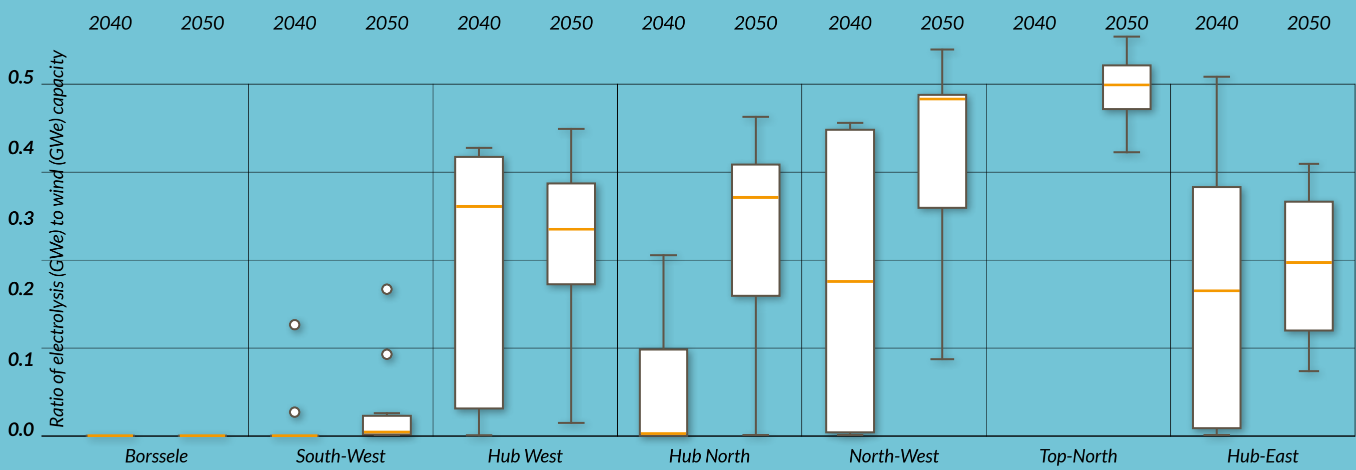


Figure 7: The ratio of offshore electrolysis to offshore wind, both in terms of their rated electrical capacity per region for 2040 and 2050 [3].



- Execution of collective research & development programs;
- Preparation of mutual pilot and demonstration projects, possibly in smaller ramping-up steps than projected before, but preferably not delayed in time;
- Pilots should be carried out in collaboration with technology providers and finance institutions in order to guarantee proof-of-concept and reduce financing costs.
- Governments around the North Sea can mutually provide clarity on future offshore electrolyser tendering capacities in order to provide long-term security for the development of an offshore electrolyser technology supply chain. Potentially, additional subsidies and support can be provided for EU-based manufacturing and technology development.

3.3 Electricity grid connection costs and utilization

The third misalignment concerns how projects are connected to the offshore electricity grid. In this analysis, it is assumed that the costs of offshore grid connections are borne by society (e.g., via the state or transmission system operator), consistent with the current Dutch regulatory framework. This assumption significantly affects the outcomes presented here and differs from other countries where such costs may fall on project developers.

Currently, offshore windfarms in the Netherlands are exempt from paying grid fees. Hence, offshore wind project developers aim to maximize their grid connection capacity in order to transmit most generated electricity to shore. However, from a societal cost perspective, it would be more efficient to allow for some curtailment and increase cable utilization by connecting wind farms to a grid cable with a smaller capacity than the wind farm itself – an approach that becomes increasingly attractive given the rising cost of electricity infrastructure. In the case of offshore electrolysis, projects are likely to minimize their grid connection if they are subject to the same tariffs as onshore electricity consumers. Yet, in cost-optimal system configurations modelled for the Netherlands, no off-grid electrolysis is observed, indicating a misalignment between project-level incentives and system-level efficiency.

3.3.1 Societal perspective

3.3.1.1 Connecting offshore windfarms

To examine the degree of undersizing across a large number of modeled offshore wind hubs and configurations as derived from all scenarios in D3.1 (such as ADAPT, TRANSFORM, and LCI), a specific metric is used. The net shore-bound electricity infrastructure for a hub is the difference between the capacity of the electricity infrastructure coming in from hubs further at sea, and the capacity of electricity infrastructure going from the hub to shore.

In the system cost-optimal results it was seen that, even without considering offshore hydrogen, generally infrastructure is undersized compared to the wind generation capacity (see *Figure 8*) unless very close to shore (see regions 'Borssele' and 'South-West')[4]. These regional labels represent a mix of existing wind farm zones (such as Borssele), planned areas from national policy, and hypothetical expansion zones developed as part of the North Sea Energy (NSE) program

4 There are two important caveats to the results, which are both consequences of the OPERA model. Firstly, since OPERA is an optimization model without stochasticity, it will install exactly the cost-optimal amount of electricity infrastructure required for the system. This is typically not a robust outcome, and changes from year to year. As a consequence, it will underestimate issues with congestion as well as unexpected system shocks or rare high-impact events. These caveats mean that the resulting capacities are likely on the lower end of a desirable, robust electricity infrastructure system. Nonetheless, the degree of undersizing is significant, with medians consistently between 60% and 80%.

Table 5: Summary of theme 3 – Electricity grid connection costs and utilization

Theme	System / societal perspective	Project developer perspective
Electricity grid connection costs and utilization	Infrastructure undersized compared to OWF capacity for societal optimal costs	OWF developer maximizes grid capacity since it is not burdened with the costs, and it minimizes electricity curtailment
	No off-grid offshore hydrogen production in system optimal results	Offshore electrolysis business case minimizes grid connection due to significant impact of tariffs
Key conclusions and recommendations	• Offshore wind (and other renewables) should be encouraged to optimize their grid capacity needs, avoiding oversized connections that are only fully utilized during peak generation periods. • Electrolysers should be incentivized when they help avoiding electricity grid reinforcements, especially when strategically located (offshore) to reduce overall system costs. • More research is needed to identify concrete interventions that promote societal optimal outcomes for project developers without leading to unintended side-effects.	

scenarios It turns out that for most wind farm locations the costs of accepting some degree of curtailment are lower than the costs of installing electricity grid infrastructure that is only utilized in the hours of peak production. The further the wind farm is located from shore, the more likely it is that the undersizing is higher. An exception is Hub North, since for this hub the transmission capacity is sometimes oversized to be able to deliver electricity to different landing points. When offshore hydrogen is considered, the system optimal electricity connections are even smaller, but overall, less electricity is curtailed.

3.3.1.2 Connecting offshore electrolysis
As discussed in *Textbox 1*, the energy system optimization with OPERA would opt for connecting smaller electrolyser capacities than those of offshore wind (ratios of 0-57% dependent on the hub location). The ratio is determined by balancing the value of being able to transport electricity to shore during low wind generation hours on the one hand, but avoiding too high infrastructure costs on the other hand. Since electricity connections are installed in all scenarios, those are utilized by the offshore electrolysers in low wind generation hours to import onshore solar electricity or electricity generated in other countries. This is seen from both an national optimal system investment perspective (OPERA) and an international optimal system dispatch perspective (I-ELGAS). This result shows providing electricity grid connections to offshore electrolysers lowers the societal costs of the energy system.

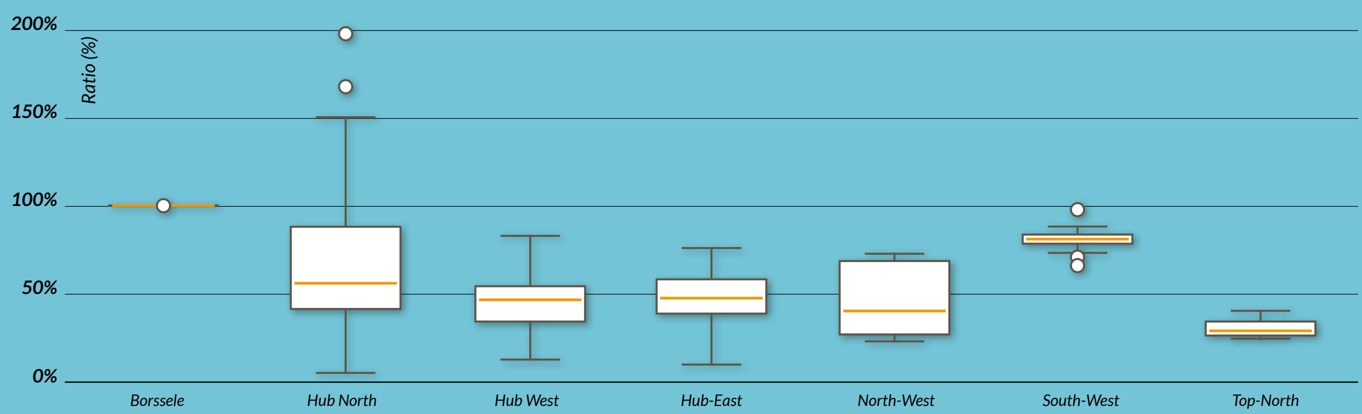
It should be noted that such a system requires both bidirectional offshore electricity cables and shared offshore grid connections between offshore wind and offshore electrolysis. While bidirectional transmission is now technically possible, further experience is needed to demonstrate its feasibility in offshore electricity systems, particularly involving offshore hydrogen production.

3.3.2 Project developer perspective

3.3.2.1 Connecting offshore windfarms
From a project developer perspective, it is difficult to imagine offshore windfarms voluntarily opting for grid connections smaller than their installed capacity. In the Netherlands, offshore windfarms currently do not pay grid fees for their connections. Therefore, choosing an undersized connection would negatively impact the project's business case by increasing curtailment and reducing revenue (see *Figure 9*). Moreover, there is no financial incentive for developers to make such a decision, as the costs of the offshore electricity grid costs are currently borne by the Dutch taxpayer.

3.3.2.2 Connecting offshore electrolysis
The business case analysis (D3.3 [5]) demonstrated that if offshore electrolysers were required to pay the same electricity grid tariffs as onshore industrial consumers, the resulting tariff costs would outweigh the additional benefits under the energy price assumptions from the infrastructure outlook scenarios (see *Figure 9*). Under such conditions, offshore electrolyser project developers would likely minimize their grid connection capacity as much as possible (while still meeting the minimum load requirements of the electrolysers). However, it is important to note that, as of spring 2025, no final decisions have been made regarding connection tariffs

Figure 8: Ratio of net shore-bound electricity infrastructure to offshore wind generation capacity for seven offshore areas of the Dutch North Sea. Results are shown for all trend-reflective scenario results [3].



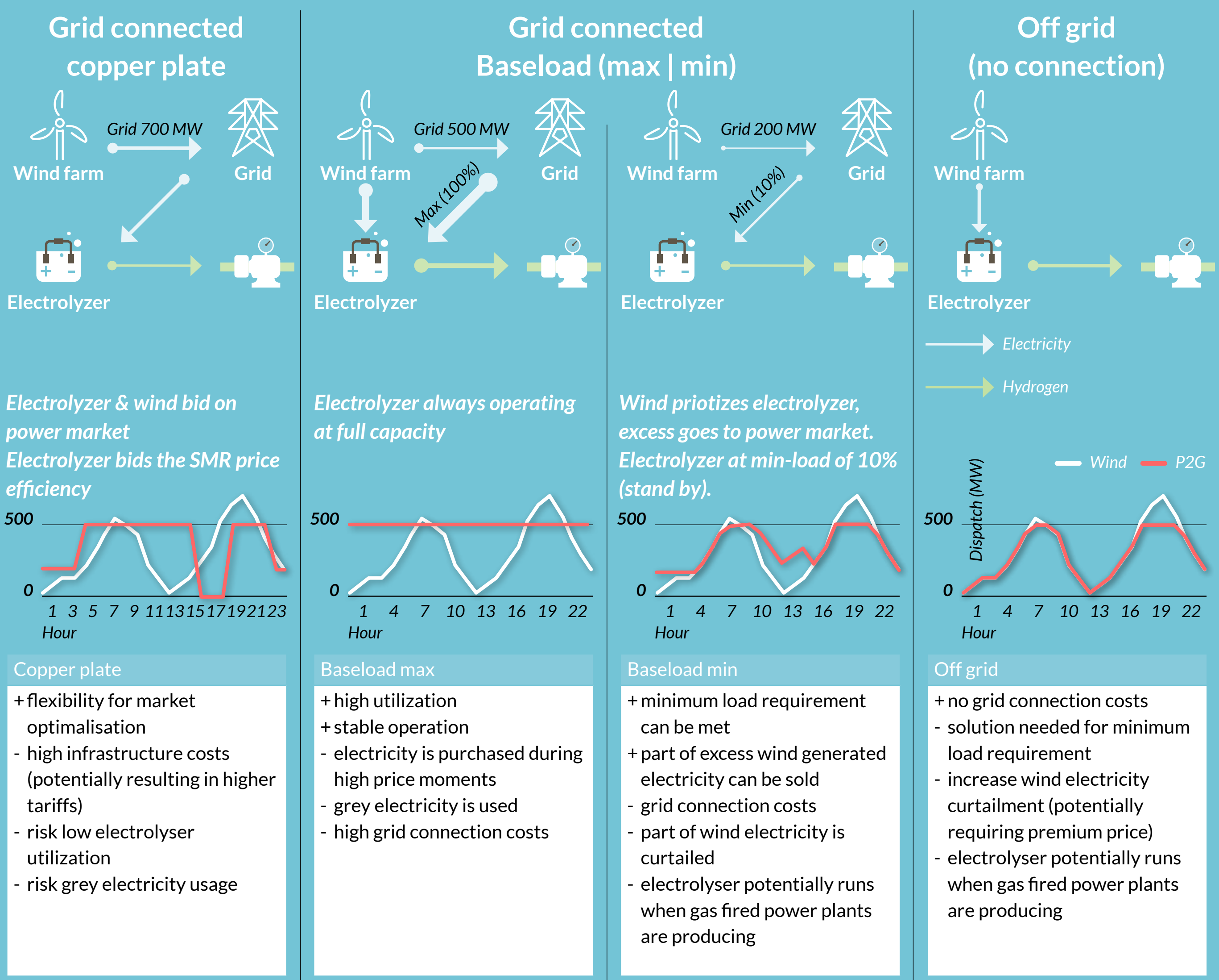
Textbox 2: Deep dive in offshore electrolysis operational strategies and its grid connection.

In [6], a deep dive was conducted into the operational strategies and connection types for offshore electrolysis (see overview Figure 10). From a business case perspective, the off-grid and minimum baseload strategies appear most favorable for electrolysers. However, these strategies lead to increased electricity curtailment, which is less beneficial for offshore wind and raises the question of whether electrolysers should compensate through a premium on electricity costs.

Another, more political consideration resulting from this assessment is that, if the off-grid and minimum baseload strategies were implemented by 2030, electrolysers would operate at times during periods when gas-fired power plants are generating electricity. This would result in a lower overall energy system efficiency compared to the "copper plate" scenario. However, the main drawback of the copper plate approach is the significant infrastructure investment it requires (costs that may eventually be reflected in future grid connection tariffs for offshore wind and/or offshore electrolysis).

The maximum baseload strategy is technically interesting but is likely less attractive from both a system and project developer perspective, due to its reliance on grey electricity and the high associated costs of electricity supply and grid connection infrastructure.

Figure 10: Overview different operational strategies and its grid connection for offshore electrolysis [6].



for offshore electrolysers. Further details on the operational strategies of offshore electrolysis and corresponding grid connection requirements are provided in *Textbox 2*.

3.3.3 Conclusion and recommendation

To conclude, there is a clear divergence between system-optimal and project developer-optimal outcomes when it comes to offshore electricity grid connections. From a societal cost perspective, undersizing the electricity grid connection of offshore wind farms would be more efficient, as it allows for higher cable utilization and cost savings. However, offshore wind developers are likely to prefer full grid connections to minimize curtailment and maximize revenue. Similarly, if offshore electrolysis is subject to the same grid tariffs as onshore electricity consumers, project developers would be inclined to minimize or even avoid grid connections (as far as possible given that electrolysers need to deal with a minimum load requirement). This stands in contrast to the societal benefit of utilizing offshore electrolysers to help balance the onshore electricity system during periods of high solar generation.

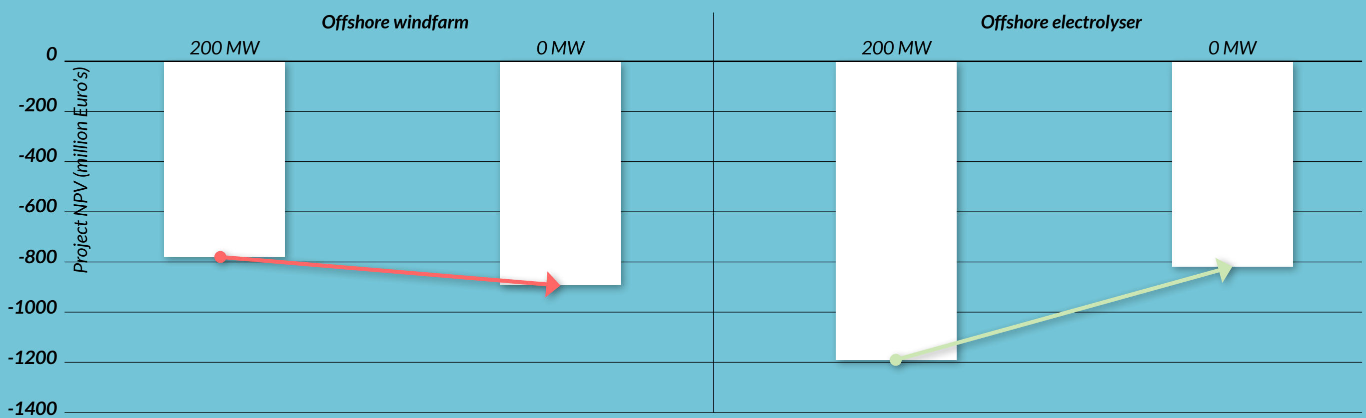
Next to misalignments between system and project developer perspectives, there are also differences between the interests of offshore windfarm and electrolyser developers. Windfarm operators currently do not incur grid connection costs, whereas offshore electrolyser developers (if subject to grid tariffs similar to those onshore) would likely minimize their connection capacity to reduce costs.

A response to these results might be to recommend on introducing feed-in tariffs for offshore wind in order to incentivize more efficient grid connection use and to support the benefits of offshore electrolysis. However, recent reports have shown that such measures could lead to unintended consequences, such as higher electricity prices, weakened business cases for existing offshore windfarms, and increased pressure on the future rollout of offshore wind capacity [12]. As a result, it is difficult to propose concrete policy solutions to close these gaps without further research into potential negative side effects.

Hence, to tackle this problem, a holistic approach is needed. Achieving a balance where both project developers maintain viable business cases while societal costs are minimized calls for several key recommendations:

- Offshore wind (and other renewables) should be encouraged to optimize their grid capacity needs, avoiding oversized connections that are only fully utilized during peak generation periods;
- Electrolysers should be incentivized when they help avoiding electricity grid reinforcements, especially when strategically located (offshore) to reduce overall system costs;
- More research is needed to identify concrete interventions that promote societal optimal outcomes for project developers without leading to unintended side-effects.

Figure 9: Impact of the electricity grid connection capacity on the levelized profits gap for the offshore windfarm and offshore electrolyser business case [5].



4.
Conclusions

This white paper highlights a fundamental challenge in the offshore energy transition: while system-level modeling points clearly toward optimal pathways for societal decarbonization, current market structures and incentive schemes do not consistently support project developers in pursuing those same outcomes. This misalignment threatens to delay investment, increase public costs, and constrain the potential of the North Sea as a renewable energy backbone for Europe.

Three areas are particularly urgent for policy attention:

- Significant offshore wind deployment is essential to achieving cost-optimal energy system transformation, yet the risk of electricity price cannibalization undermines the financial viability of new projects. Policy makers must stabilize investment conditions through mechanisms such as contracts for differences, flexible demand simulation, and coordinated tender timelines for electricity supply and demand.

- Offshore electrolysis holds significant systemic benefits such as reducing electricity grid reinforcement costs (onshore and offshore), curtailment, relieving grid congestion, saving scarce onshore space and likely saving societal energy costs. However, currently it remains commercially unattractive without intervention. Tailored support instruments, strategic infrastructure planning, and predictable offshore hydrogen tender volumes are needed to guide the technology through its "valley of death" and into scalable deployment. Additionally, the sizing ratio between offshore wind capacity and electrolysis capacity emerged as a critical design parameter for aligning societal value and project developer incentives: smaller electrolyser-to-wind ratios can improve utilizaiton, lower hydrogen cost requirememnts, and help bridge the gap between societal value and viable project economics especially in early demonstration phases.

- Grid infrastructure planning currently entails almost full-capacity connections, driven by zero-cost access for offshore wind developers. However, a societal cost-optimal system would often favor partial connections and integrated design with hydrogen production. Incentivizing efficient grid use, other than just modifying tariff structures, can unlock system benefits while ensuring fair cost distribution.

Across all themes, the analysis underscores the need for coordinated policy intervention to bridge the gap between public value and private investment logic. Selecting the right mix of policy intervention is neither simple nor arbitrary. While this paper offers concrete recommendations, it also highlights several issues that remain unresolved and require further exploration:

- To what extent do high renewable energy scenarios offer long-term, feasible business cases for all essential components under the current market framework, especially given uncertainties around future cost developments?
- What specific interventions can be implemented to reward electrolysers for helping to avoid electricity grid reinforcements, and how can offshore wind be encouraged to optimize grid utilization?
- How does the optimal scaling of offshore wind and electrolysis appear from a project developer's perspective, and can this help reduce the need for prolonged support in advancing offshore electrolysis?

Left unaddressed, these misalignments could undermine the affordability and feasibility of the offshore energy transition. But with the right policy frameworks, governments can unlock mutual benefits: accelerating decarbonization, promoting technological leadership, and safeguarding the long-term resilience of Europe's energy system.

As the North Sea becomes a cornerstone of Europe's climate and industrial policy, this calls for integrated governance across electricity, hydrogen, and infrastructure planning. A proactive and adaptive policy approach co-created with industry, informed by system analysis, and aligned cross borders will be essential to achieving societal value without stalling private initiative.

References

[1] D. Loorbach, N. Frantzeskaki en F. Avelino, „Sustainability Transitions Research: Transforming Science and Practice for Societal Change," Annual Reviews, 2017.

[2] A. Nijhof, A. Wins, A. Argyrou en N. Chevrollier, „Sustainable market transformation: A refined framework for analyzing causal loops in transitions to sustainability," Environmental Innovation and Societal Transitions, 2022.

[3] S. Blom en J. Stralen, „Public Value Assessment," NSE5, 2025.

[4] R. v. Zoelen, S. Mahfoozi, D. Boer en N. Dooley, „Business models for value chains for new offshore energy concepts," NSE5, 2025.

[5] R. v. Zoelen, D. Boer en S. Mahfoozi, „Business case assessment for the offshore value chain," NSE5, 2025.

[6] I. Gonzales-Aparicio, M. Wevers en R. Aitazaz, „Scaling Offshore Wind-to-Hydrogen Systems: A Pathway to Feasibility and Integration by 2050," NSE5, 2025.

[7] Netbeheer Nederland, „Het energiesysteem van de toekomst: de II3050-scenario's," Netbeheer Nederland, 2023.

[8] ENTSO-G & ENTSO-E, „TYNDP 2024: Scenarios Report," 2024.

[9] J. Stralen, J. Sipma en J. Gerdes, „An analysis of the value of offshore hydrogen production in relation to alternatives," NSE3, 2020.

[10] M. v. Schot en C. Jepma, „A vision on hydrogen potential from the North Sea," NSE3, 2020.

[11] Centraal Bureau voor de Statistiek, „Nearly half the electricity produced in the Netherlands is now renewable," Centraal Bureau voor de Statistiek, 07 March 2024. [Online]. Available: https://www.cbs.nl/en-gb/news/2024/10/nearly-half-the-electricity-produced-in-the-netherlands-is-now-renewable. [Geopend 07 May 2025].

[12] Aurora Energy Research, „Feed-in grid charges - policy assessment | Policy note," 2024.

As the North Sea becomes a cornerstone of Europe's climate and industrial policy, this calls for integrated governance across electricity, hydrogen, and infrastructure planning.

North Sea Energy
offshore system integration

Design; www.knoeff.nl

North Sea Energy offshore system integration