North Sea
Wind Power Hub
Programme

System integration

Integration of offshore wind

How flexible consumption could benefit the integration of large-scale offshore wind

Discussion paper

#1

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About this paper

Why read this report

The European Commission aims for net zero greenhouse gas emissions in 2050 in Europe. Large-scale offshore wind will play a large role in fulfilling this goal and should therefore efficiently be integrated in the energy system.

This paper is the first of two papers which aim to empower policy makers in their decision-making by facilitating an objective and balanced discussion. The first paper sets the scene and shows the need for large-scale flexible electricity consumers and gives insight in the role of Power-to-X (PtX) by explaining what it is and in what ways it can help the energy system. It will provide four guiding principles for efficient integration of offshore wind in the energy system.

The second paper will discuss incentivization of optimal renewable energy (system) usage through market design and regulatory principles.

Highlights

The consortium has identified four guiding principles for the integration of large scale intermittent renewable energy:

1. **A timely development of a hydrogen market and infrastructure;**
2. **Mechanisms which provide incentives for efficient locations for electrolysis from an energy infrastructure perspective;**
3. **Mechanisms which support timely construction and upscaling of electrolysers;**
4. **Market and regulatory mechanisms which provide dispatch incentives to improve optimal usage of renewable energy and infrastructure.**

Structure of the discussion paper

1. Introduction
2. Integration of large-scale offshore wind
3. Flexible electricity consumers
4. Sector coupling
5. Imported hydrogen
6. Four guiding principles
7. Conclusion

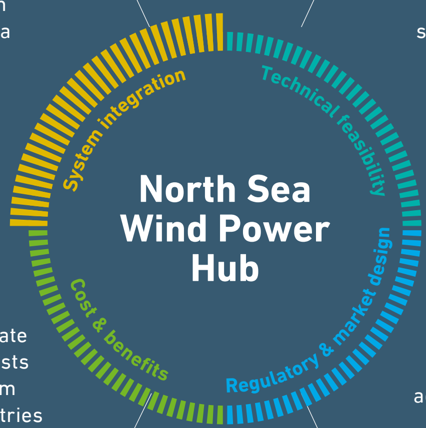
The big picture

The North Sea is a powerhouse of wind energy. Harnessing this power requires us to cooperate across countries and borders to build an efficient network. To show that a solution can be achieved in a cost-effective and secure manner, the North Sea Wind Power Hub is working within four key areas.

This discussion paper explores key topics within system integraton.

How to adapt the energy systems in Northern Europe to integrate a large volume of offshore wind from the North Sea.

How to design and build the physical hubs and spokes that will collect, transform and distribute energy from the North Sea.



How to ensure that the chosen solution maximises benefits for society and climate while minimising costs and distributing them fairly between countries and stakeholders.

How to ensure a stable and reliable investment climate by adapting regulation and creating an efficient market design.

Executive summary

The deployment of renewable energy sources in Europe will increase significantly to support the goal of net zero greenhouse gas emissions by 2050. Offshore wind will have a large part in this, as the European Commission stated in its offshore renewable energy strategy that a target of 300GW in 2050 is realistic and achievable.[1] To enable this rapid acceleration in deployment and integration of large-scale offshore wind, with maximum socio-economic benefit, there is an urgent need for international coordination, combining grid connection for offshore wind, interconnection functionality and sector coupling.

This paper aims to set the scene and show the need for large-scale flexible electricity consumers (i.e. usage by final consumers, but also conversion and storage) to efficiently integrate large capacities of offshore wind energy into the European energy system, and gives insight in the role of Power-to-X by explaining what it is and in what ways it can help the energy system. Direct (batteries, electric vehicles, heat storage) and indirect (electrolysers) electrification provides the energy system with flexibility enhancing a further system integration between power, heat and gas. Main focus of the paper will be on indirect electrification e.g. electrolysis.

Allowing for large-scale flexible electricity consumption, will:

1. reduce the cost of grid reinforcements;
2. support the economic viability of intermittent renewable energy deployment;
3. increase the share of intermittent renewable electricity capacity;
4. enable additional build out of offshore wind, which supports more electrification while enabling decarbonization of hard-to-abate sectors;
5. reduce curtailment of offshore wind, and;
6. function as seasonal storage.

Furthermore, import of green hydrogen into the EU from surrounding countries is expected. Its extend will be based on cost reductions and will be subject to market dynamics and pricing.

[1] An EU strategy to harness the potential of offshore renewable energy for a climate neutral future, 2020 (link).

The consortium has identified four guiding principles for the integration of large scale intermittent renewable energy in the energy system:

1. A timely development of a hydrogen market and infrastructure (both within and between regional, industrial clusters);

2. Mechanisms which provide incentives for efficient locations for electrolysis from an energy infrastructure perspective;

3. Mechanisms which support timely construction and upscaling of electrolysers by e.g. providing investment certainty allowing to kick start large scale flexible consumption;

4. Market and regulatory mechanisms which provide dispatch incentives to improve optimal usage of renewable energy and infrastructure.

The North Sea Wind Power Hub (NSWPH) aims to analyse potential market designs and regulatory framework principles to facilitate an efficient and effective electrolysis roll-out to realise an efficient cross-border and cross-sectorial energy system with maximum usage of renewable energy and net socio-economic benefits for consumers, producers and other stakeholders. This should also include a broad exploration on roles and responsibilities of all stakeholders for electrolysis and other methods to provide incentives for efficient location and timing of conversion while supporting investment security.

1 Introduction

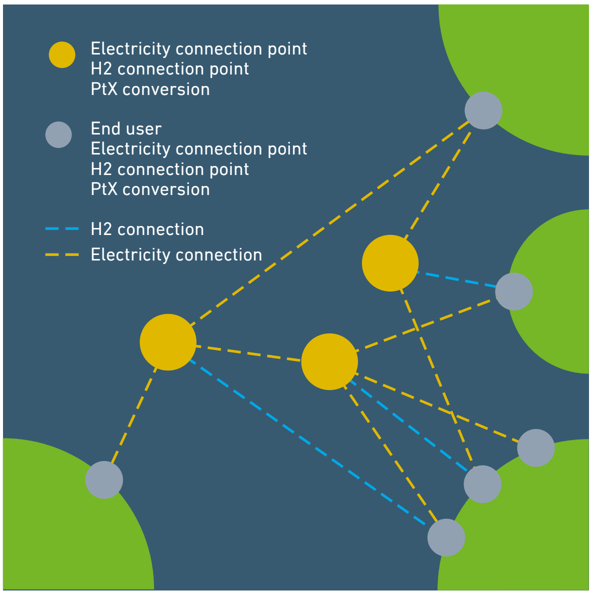
The Paris Climate Agreement sets out a global framework to avoid climate change by limiting the rise of the global temperature to well below 2°C and pursuing efforts to limit the temperature increase to 1.5 °C. To keep the promises made in the Paris Agreement, a significant decarbonisation challenge lies ahead of us.

Large-scale offshore wind deployment in the North Sea has a significant potential for providing a cost-efficient decarbonisation pathway for the North West European (NWE) energy system. To meet the Paris Agreement, the European Commission estimates that at least 300 GW of offshore wind power is necessary by 2050, of which approximately 180 GW of offshore wind power capacity can be installed in the North Sea by 2050.[2] According to the European Commission's Energy System Integration Strategy, coupling of energy systems and conversion of electricity to other energy-carriers will be necessary to:[3]

1. reduce greenhouse gas emissions from sectors that are hard-to-abate;
2. provide required demand and supply flexibility to deal with the intermittent nature of some renewable energy sources; and;
3. maintain system resilience and security of supply.

Highlight
Large-scale offshore wind projects are necessary to meet the goal of net zero greenhouse gas emissions by 2050.

Figure 1: Hub and Spoke project



In hybrid projects, as the Hub-and-Spoke project, offshore wind grid connection and interconnection are combined. Electrolysis can be added either onshore or offshore to facilitate incorporating the large capacities of offshore wind in the European energy system.

[2] European Commission: An EU strategy to harness the potential of offshore renewable energy for a climate neutral future, 2020.(link) Navigant: Integration routes North Sea offshore wind 2050, 2020.(link)
[3] European Commission: Powering a climate-neutral economy - an EU strategy for energy system integration, 2020.(link)

The aim of the North Sea Wind Power Hub consortium is to facilitate an accelerated deployment of large-scale offshore wind in the North Sea with minimum environmental impact and at the lowest cost for society, while maintaining security of supply. The solution is twofold:

- Combining offshore wind grid connection with efficient landing and interconnection of EU electricity markets in hybrid projects in order to maximise efficient use of electricity;

- Coupling energy sectors at scale to enable energy system integration and provide large scale flexibility (see Figure 1).

To enable hybrid, cross-sector projects ("hubs") to connect and integrate large scale offshore wind, it is necessary to understand the need for sector coupling and to kick-start and facilitate structured discussions on key regulatory, legal, and commercial aspects. The aim of such discussions is to establish agreements and legal frameworks that align interests and provide certainty for Member States, project developers and other stakeholders. Therefore, the consortium will publish two discussion papers intended to provide a thorough knowledge basis on system integration of large-scale offshore wind. The present paper with an energy system perspective will focus on the entire value chain and will explain the need for flexibility, sector coupling and electrolysers in a future energy system. Furthermore, it will provide four guiding principles for efficient integration of offshore wind in the energy system. The second discussion paper will be based on the present paper and will dive deeper into key market and regulatory principles that can support an efficient integration of offshore wind in the energy system by network infrastructure companies.

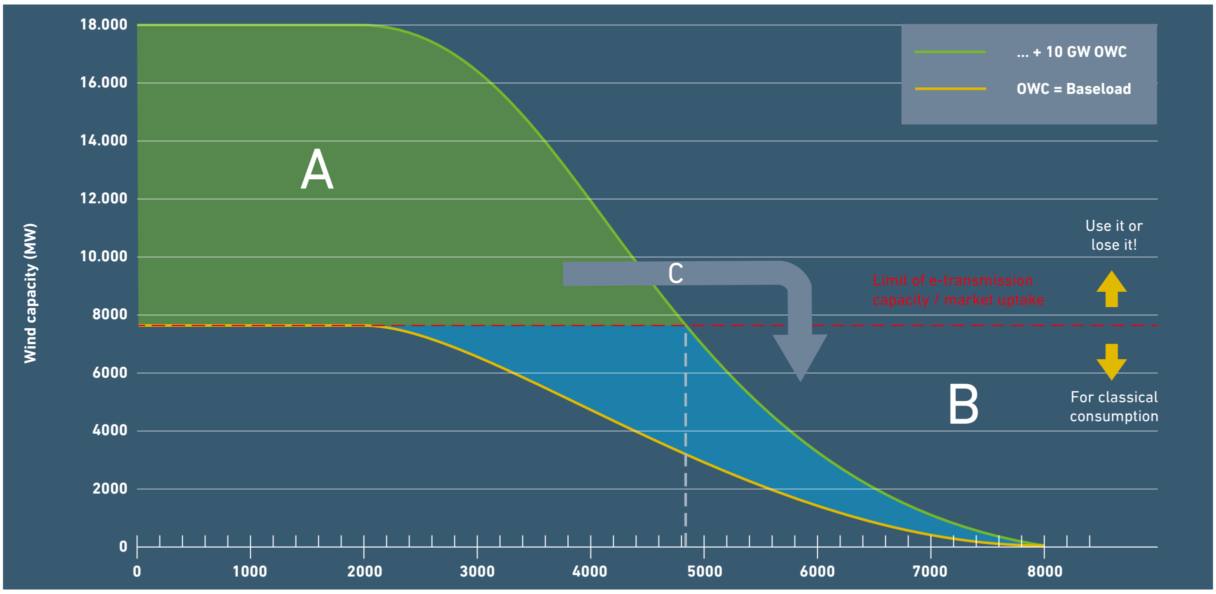
Power-to-Gas-to-Power (PtGtP) i.e. reconversion of hydrogen to power, will be discussed in a future (third) paper.

2 Integration of large-scale offshore wind

One of the challenges related to a massive build out of offshore wind is that the capacity of the current electricity grids is limited compared to the above-mentioned offshore wind capacity targets of the European Commission.[4]

Another challenge is balancing the production and consumption of electricity with increasing capacities of non-dispatchable electricity resources and inflexible consumption. Thus, increasing the capacity of the electrical infrastructure does not solve all challenges in relation to the integration of large scale offshore wind. To illustrate this; a duration curve sketch for wind power production from Denmark is used as an example, see Figure 2.[5] Today, wind power (yellow curve) has been deployed to an extent where a few days of Danish peak electricity consumption (red dashed line) can be fully supplied. In this sense the red dashed line also illustrates the capacity of the current electricity grid.

Figure 2: Wind duration curve



Wind duration curve (yellow and green curve) and a transmission capacity limit/a simplified stable electricity consumption (red dashed line). The blue area opens as a cheap electricity source (compared to dispatchable power) for electricity consumers when additionally building out wind compared to the grid capacity. The green area is available for flexible consumers located at or near the feed-in point to the main electricity grid. An economic viable utilisation of most of the electricity in the green area is also a precondition for an economically viable additional buildout of wind. A, B, and C depict three types of flexibility which can benefit the integration of large-scale offshore wind, see further explanation in Section 2.

[4] See appendix A for an overview of national and supra-national offshore wind capacity targets.
[5] Curve where electricity production capacities for each hour of the year is arranged from highest to lowest.

With the aid of a large-scale flexible consumer located close to the feed-in point of large-scale offshore wind energy to the main electricity grid, it is possible to build additional offshore wind compared to the grid capacity. Additional buildout refers to a situation in which the offshore wind capacity exceeds the transmission capacity of the main grid. Additional buildout in combination with flexible consumption enables that more hours of the classical electricity demand can be directly covered with wind energy (blue area) instead of e.g. fossil fuels. It also leaves a potential that can only be efficiently utilised close to the generation source (green area).

Highlight
Flexible consumption and additional buildout of offshore wind allow for coverage of electricity demand directly with wind energy.

Without flexible consumption, additional buildout results in situations with excess energy which causes a price drop and several hours with low or close to zero electricity prices. Adding flexible consumption creates electrical demand at moments of high electricity production by volatile renewable energy sources, which creates more price stability and increases electricity prices at those moments. Increasing electricity prices result in higher captured revenues for offshore wind farms, which is, together with price stability, an important factor in the business case and therefore could potentially support further offshore wind deployment.

3 Flexible electricity consumers

An efficient transition towards a renewable energy system will benefit from two different types of flexible electricity consumption: large-scale flexible electricity consumption (A in Figure 2) and demand response within the current grid (B in Figure 2) Another type of flexibility is time-shift flexibility which is marked as C.

The A-type is large-scale flexible electricity consumption which is placed on the border of the existing electricity grid to prevent congestions in the grid and to allow an economically viable additional buildout of intermittent renewables (green area in Figure 2). This type of flexibility can both be used for sector coupling (see Section 3) and for time-shift flexibility. New additional transmission lines could also enable the utilisation of the "excess" electricity at large demand centres. The issue is that the utilisation rate of potential additional transmission lines would be low, which would significantly increase the cost per MWh of this option, compared to an A-type flexible electricity consumption before the electricity enters the main grid. The A-type of flexibility is characterised by a limited and fragmented number of operating hours where the transmission grid capacity cannot transport all produced electricity.

The B-type of flexible consumption of electricity is the flexibility from demand response within the current grid i.e. the ability to stop using electricity when the supply of intermittent renewables is limited. This type of flexibility will decrease the demand for dispatchable power which is often more expensive and less efficient than intermittent renewables. Figure 2 also illustrates how the A-type of flexibility would help to decrease the number of hours where the B-type of flexibility is needed. This will enable more direct electrification as the number of hours with high electricity prices due to dispatchable power production will decrease.

Highlight
There are three types of flexibility: large-scale flexible electricity consumption, demand response within the current grid and time-shift flexibility.

The last type of flexibility shown in Figure 2 is the time-shift flexibility, C-type. This is the ability to store electricity in periods with a surplus/usually low prices (same as the A-type) and deliver it back in periods with deficits/usually high prices (instead of the B-type flexibility). It has been demonstrated that there is a need for long term/seasonal flexibility.[6] This can be provided by PtGtP, which is both feasible and cost-effective.[7] This type of flexibility can also be a benefit for the integration of large amounts of intermittent electricity, but it would, due to conversion losses, be most efficient first to use the A- and B-type of flexibility, which would decrease the need for the C-type flexibility.[8]

[6] Navigant: Integration routes North Sea offshore wind 2050, 2020.(link)
[7] Navigant: Integration routes North Sea offshore wind 2050, 2020.(link)
[8] As mentioned before, PtGtP will be discussed in a future discussion paper.

Table 1: Relative magnitude A, B and C

The below table gives an indication of the relative magnitude of A, B and C for a fictional energy system.

Total production	80,96	TWh
A-type	33,76	TWh
B-type	22,87	TWh
C-type	22,87	TWh
Direct eletrification from wind	47.21	TWh

Note that B and C are maximal values, they could also be zero(!) depending on the size of the other and the actual demand pattern. It seems that B and C in reality are likely half the size of their maximum. Furthermore, B and C "share the same space", thus the actual values would be around 5 TWh of C and 5 TWh of B if an equal split is assumed for this fictional energy system. In this case A would also be bigger than stated above, but this extra demand can be located within the grid as this "oversupply" compared to the actual demand "fits" within the grid.

Electrolysers are expected to have the biggest potential in relation to the A-type of flexibility where electrolysis is used as a solution to integrate large amounts of offshore wind power in the electricity system.[9] Electrolysers use electricity to split water into hydrogen and oxygen. Hydrogen can be used as a fuel itself, refined into other energy carriers, or be converted back into power. Furthermore, hydrogen, can be transported over long distances through pipelines and stored for long periods of time (months/years) in e.g. salt caverns, at lower costs than electricity. Thus, a landing point for large-scale offshore wind does not necessarily have to be co-located with demand other than an electrolyser with a hydrogen pipeline available. If the landing points are co-located with other energy demands such as industry, heat production from heat pumps or electric boilers could for example also provide the same A-type flexibility as electrolysers depending on the storage options and utilisation patterns.

The A-type flexible consumption is also a tool to increase the potential for direct electrification using wind and solar (blue area in Figure 2). For electrolysis, we denote the process "system integration of electrolysis" when additional buildout and flexible consumption is continued until overall system cost is optimised. When sourcing electricity for electrolysis using system integration, cheap electricity will be available (<LCOE).[10] It is physically possible to continue buildout beyond the optimal level. However, ultimately electricity for electrolysis will cost-wise arrive at LCOE for the generation source – this part we denote "dedicated additional buildout with flexible consumption". This is especially relevant to consider in relation to import of hydrogen which is discussed in Section 4.

[9] Navigant: Integration routes North Sea offshore wind 2050, 2020.(link)
[10] Levelized Cost of Energy i.e., lifetime costs divided by energy production.

The B-type of flexibility is assumed to be provided from consumption that does not violate the transmission capacity of the electricity grid. Thus, the providers can be spread throughout the existing grid which enables flexible consumption from heat pumps, electric boilers, battery electric vehicles, industrial processes, electrolysers etc. Figure 2 shows that the number of hours where this type of flexibility is needed decreases as more wind power is being integrated, thus shorter-term flexibility is often enough and could for example be provided by power-to-heat through:

1. Industry. In many industrial sectors there is a potential to electrify more of the processes. Especially for heat production at lower temperatures. Depending on the process and the configuration of the installation, some shorter term flexible electricity consumption can also be provided here.

2. Individual households. It is possible to store energy in the thermal mass of buildings and in their hot water tanks. Therefore, it is possible to turn off electric heating devices for some hours depending on the outside temperature and weather conditions. This gives a short term flexibility for electricity consumption.

3. District heating. Many current district heating facilities have a hot water storage tank to buffer production for some hours or days. If heat is produced from electric heating devices these current storage facilites can also give some flexibility in the electricity consumption. The interest for seasonal heat storages is also increasing and these storage facilities would give a bigger flexibiltity potential for electricity consumption for heat production.

4 Sector coupling

The above explained requirement for more flexibility leads to further integration between energy sectors e.g. hydrogen from electrolysis for the industry, electric vehicles in the transport sector and heat pumps in the heating sector.

The first example, hydrogen from electrolysis, is an example of indirect electrification, while the two last are examples of direct electrification. Direct electrification based on intermittent renewables is often the most efficient way of providing energy system end-services such as mobility and heat, but the flexibility in time and scale is limited compared to electrolysis.[11]
The European Commission estimates that in 2050, under their 1.5 scenarios, direct electrification will supply close to 50% of the final energy consumption, while the remaining 50% is expected to be supplied from fuels such as biomass, e-gasses, e-liquids, but also a small amount of fossil fuels.[12] Today electricity supplies around 25% of the final energy consumption in the EU.[13] To obtain this high share of direct electrification from intermittent renewables (yellow area in Figure 2) and to decarbonize the economy, a great number of different flexibility options is necessary. Sector coupling through electrolysis ensures that offshore wind capacity in the North Sea can be integrated efficiently with little discarded electricity, by enabling synergies across energy sectors, while ensuring security of supply of affordable energy and cost savings for the energy infrastructure.[14]

As mentioned earlier, the system integration with electrolysis should take place close to generation, to avoid excessive build-out of electricity infrastructure. In practice this could be in landing zones for the first hubs, and potentially offshore for the later hubs. In landing zones excess heat from the electrolytic conversion will be available and utilising it would increase the efficiency of the entire system. Connecting large-scale photovoltaics (PV) to landing zones could also become interesting as wind and solar are quite asynchronous; on windy days, the sun usually doesn't shine and vice versa, therefore these two sources are complementary.[15]

Highlight
System integration with electrolysis should take place close to generation, to avoid excessive build-out of electricity infrastructure.

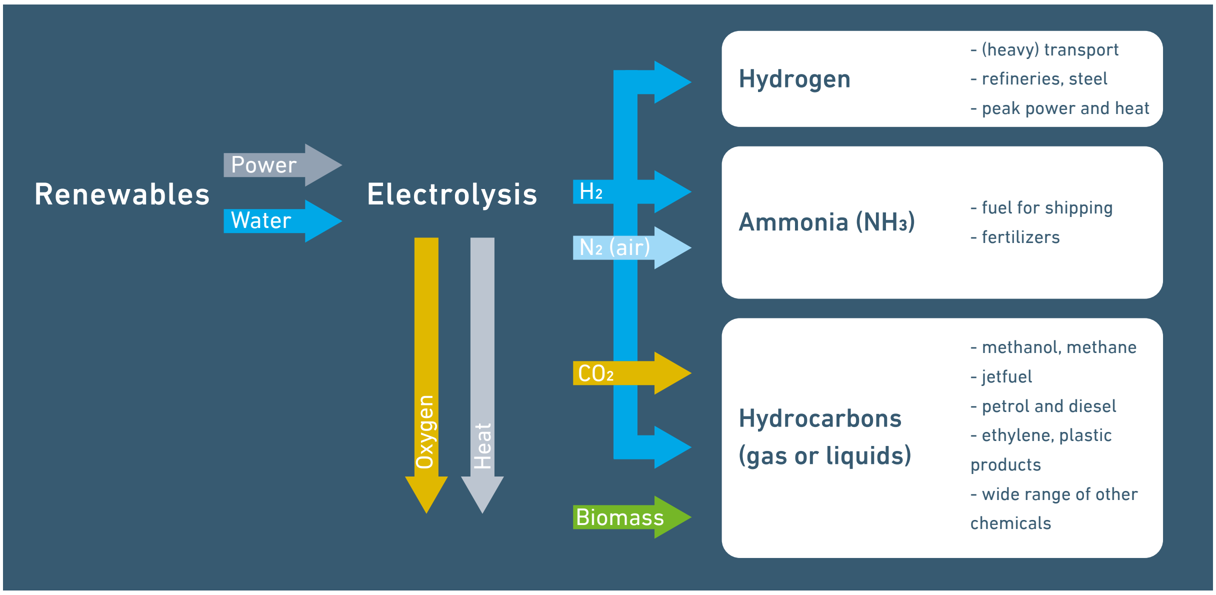
[11] European Commission: In-depth analysis in support of the commission communication COM(2018) 773 - A clean planet for all - a European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, 2018. (link)
[12] European Commission: In-depth analysis in support of the commission communication COM(2018) 773 - A clean planet for all - a European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, 2018. (link))
[13] European Commission: In-depth analysis in support of the commission communication COM(2018) 773 - A clean planet for all - a European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, 2018. (link)
[14] For an economically optimised system, curtailments of intermittent renewables will take place as it is not economically viable to build grids or flexible consumption for the hours with absolute peak production.
[15] Energinet: Energikoncept 2030, 2015. (link)

5 The role of imported hydrogen

Through direct and especially indirect electrification, wind and solar power has the potential to enter almost all sectors of society. The potential applications for indirect electrification, i.e. utilizing hydrogen from water electrolysis, are vast.

Through electrolysis power can be turned into a wide variety of chemical compounds. Figure 3 is an illustration of the value chain of some of these compounds and their applications. The umbrella term PtX is often used to describe this conversion of renewable power via electrolysis into different chemical compounds as illustrated.

Figure 3: Potential PtX value chains



The PtX value chain showing the different conversion options and potential utilisations of end-products.

The question here is to what extent these chemical compounds should be produced locally or imported. System integration of electrolysis is an argument for local production, but the value of this decreases as the scale of additional buildout goes towards dedicated hydrogen production. At some point it would likely be cheaper to import hydrogen e.g. via pipelines from Northern Africa or via ship from all over the world (see Figure 4). An efficient market could provide the right incentives to strike this balance of import and local production.

Furthermore, the competitiveness strongly depends on the cost of offshore wind (and onshore wind and sun) in North West Europe versus onshore wind and solar cost in the exporting countries. Here production and transport costs together with security of supply considerations will determine the level of import. The cost of imported green hydrogen can be competitive compared to hydrogen produced by offshore wind farms in the North Sea, as shown in Figure 5.[16] Here the circles illustrate the price sensitivity related to the assumptions made for the cost of producing green hydrogen and the transportation of it.

Figure 4: Possible hydrogen import routes

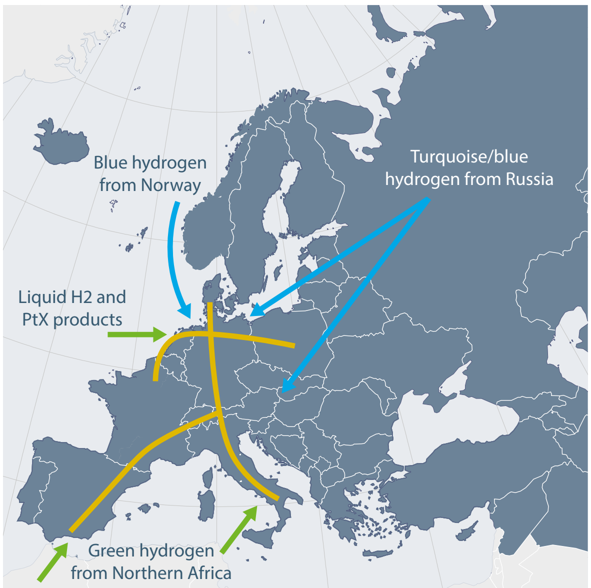
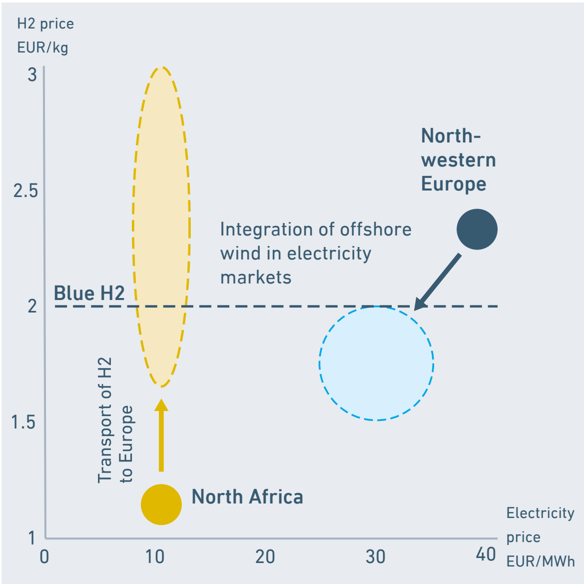


Illustration of possible hydrogen import routes for blue and green hydrogen to Europe via pipelines and ship. The yellow line illustrates one European 'hydrogen backbone'.[17]

Figure 5: Comparison estimated production costs of hydrogen in NEW and Northern Africa in 2030.



Estimated production costs for hydrogen in NWE and Northern Africa in 2030, respectively, showing cost of transportation cost from Northern Africa and system integration in NWE.[18]

[16] Energinet and the Danish Energy Association: Gamechangers for PtX and PtX infrastructure in Denmark, 2020. (link)
[17] Enagás, et al: European hydrogen backbone - how a dedicated hydrogen infrastructure can be created, 2020. (link)
[18] Energinet and the Danish Energy Association: Gamechangers for PtX and PtX infrastructure in Denmark, 2020.(link)

6 The four guiding principles for integrating large-scale offshore wind

The foregoing discussion clearly illustrates the added value of electrolysers and other flexible electricity consumers for an integrated, reliable energy system. However, to reach an efficient cross-border, cross-sector energy system with maximal usage of renewable energy and net socio-economic benefits for consumers, market designs and regulatory frameworks should provide balanced and appropriate incentives for investment.

There is especially a clear need for:

1. A timely development of a hydrogen market and infrastructure (both within and between regional, industrial clusters);
2. Mechanisms which provide incentives for efficient locations for electrolysis from an energy infrastructure perspective;
3. Mechanisms which support timely construction and upscaling of electrolysers by e.g. providing investment certainty allowing to kick start large scale flexible consumption;
4. Market and regulatory mechanisms which provide dispatch incentives to improve optimal usage of renewable energy and infrastructure.

5.1. Development of a hydrogen market and infrastructure

There are many ambitions and roadmaps for increasing the installed electrolyser capacity throughout Europe. For all countries the same phenomenon appears. Since many ambitions were only recently established, there is a large gap between these ambitions and the actual realisation. One of the central questions is how to scale up from ~0 to 40GW of electrolysis equipment in Europe before 2030.[19] Hydrogen infrastructure is needed to develop a mature European market for green hydrogen. But without any green hydrogen production and enough green hydrogen demand, the need for hydrogen infrastructure is not present. Hence, there is a need for the coordinated development of an EU wide hydrogen market and infrastructure (both regional infrastructure in industrial clusters and connections between these clusters), including clear roles and responsibilities in order to make the market function efficiently.

Highlight

The consortium has developed four guiding principles for an efficient cross-border and cross-sector energy system.

[19] European Commission: A hydrogen strategy for a climate-neutral Europe, 2020.(link)

Possible steps are the inclusion of an integral on- and offshore infrastructure planning development plan, jointly developed by ENTSO-E and ENTSOG, including optimization options for the required on- and offshore electricity and gas (hydrogen) infrastructure in the revision of the TEN-E Directive and the provision of a long-term horizon, a clear regulatory framework for transport and storage plus financial instruments to ensure timely development of a hydrogen market and infrastructure.

When developing the infrastructure and a hydrogen market, some points are important to keep in mind:

1. Principles of the market. A well-functioning hydrogen market, with sufficient supply and demand, should incentivize socio-economic welfare maximization as a consequence of efficient dispatch of production assets. The dispatch and investment should be efficient in location, timing of the construction and operation.[20]

2. Equipment and retrofitting. Making existing gas assets and technologies such as compression, transport infrastructure and storage suitable for hydrogen also has its challenges. Retrofitting requires technical system adaptations especially in the field of subsurface hydrogen storage, compression, cleaning of existing pipelines and the "soft" parts of the transport equipment like valves and measurement equipment.

3. Quality requirements. To ensure the development of a European hydrogen market, exchangeability of hydrogen is of the utmost importance. Therefore, not only the technical grid development should be considered, but also quality requirements i.e. both the hydrogen purity and the composition of the impurities and trace components. This should be similar to quality requirements for natural gas in the current gas grids. The quality specifications at a given moment in time should be optimized from a socio-economic point of view between supply and demand (including a capacity-based analysis) and might therefore change over time as the market develops and matures.

Since the wind and hydrogen industry is very international, the crucial innovations can be expected in different geographical and functional areas. The best international innovative solution might realise breakthroughs. Based on current technology with related cost levels, together with the fossil and CO2 pricing, it is still expected that market and regulatory mechanisms are necessary to provide investment certainty to stimulate this industry. Besides this, governments should promote innovations and pilot projects related to electrolysis by providing subsidies for research and demonstration projects supporting upscaling of electrolysers.

[20] Handelsblatt: Uberlebensfrage Wasserstoff, 2020, October 5.

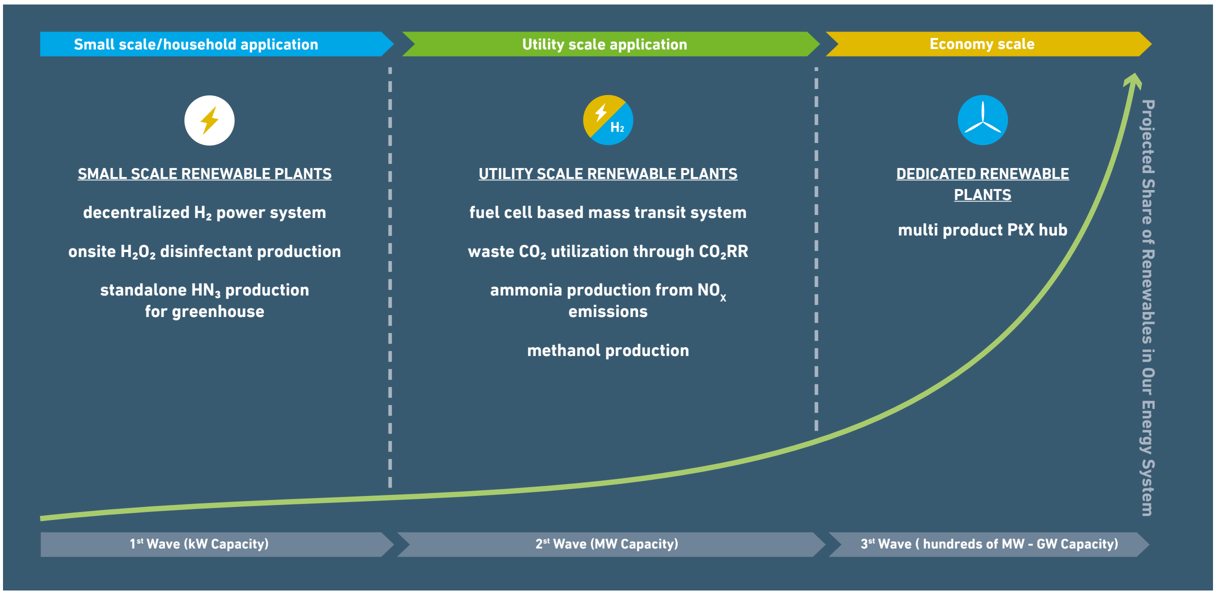
5.2. Location

The previous sections and the Infrastructure Outlook 2050, suggests that it appears to be most efficient to place electrolysers close to renewable electricity generation.[21] Existing gas infrastructure in the proximity to landing points could then be beneficial to reuse for hydrogen transport. On the other hand, inefficient placing of electrolysers could cause major grid challenges, e.g. congestions, with economic and climate impacts. Combining planning of electricity grids, gas grids, and electrolysis on a national and European level therefore seems pivotal. Hence, development and publication, as part of an integral on- and offshore infrastructure planning development plan per sea basin and the national development plans, of a map with efficient locations for electrolysis considering the overall system costs and internalising the cost on the short run. The market design could efficiently indicate the right locations for investments in electrolysis. In addition, the real cost should be internalised in the transport tariffs e.g. optimal placing of electrolysis should be reflected in the transport tariffs for producers.

5.3. Upscaling and construction

Upscaling the electrolysis to a size that is useful for balancing renewable power is ongoing but is a process that requires time. Despite the relatively high technological readiness level of small-scale electrolysis, significant steps need to be taken in order to reach GW scale electrolysis. The main challenges in the technological development of GW scale electrolysis are the costs of producing hydrogen at a large scale and the competition and production costs of these green molecules compared with the fossil-based alternatives including CO_2 taxation. It is expected that upscaling of electrolysers roughly follows a path as illustrated in Figure 6. The development of electrolysis and its penetration into the energy system is following a pattern through time – or waves of technologies.

Figure 6: Development of electrolysis and PtX technologies.



The relative development of electrolysis and Power-to-X technologies.[22] Note: this includes more than just conversion to H_2.

[21] Gasunie and TenneT: Infrastructure Outlook 2050 - a joint study by Gasunie and TenneT on integrated energy infrastructure in the Netherlands and Germany, 2019.(link)
[22] Daiyan, MacGill & Amal: Opportunities and challenges for renewable Power-to-X, 2020.(link)

The need for electrolysis at utility scale seems to be acknowledged throughout the world, with at least 192 electrolysis demonstrations identified in 2019.[23] However, as was found in 2018 and is still relevant today, there are no satisfactory business cases for electrolysers: hydrogen production prices are still higher than the commodity prices of the gas, even under relatively optimistic circumstances.[24] These commodity prices should increase for a positive business case.[25] This conclusion indirectly captures several challenges for electrolysis currently. The business case for electrolysis, as was summarised by North Sea Energy 2020, is influenced by key factors as:

- **Capital investment costs** | the higher, the worse the business case assuming similar full load hours. Mainly focused on the costs for electrolysers.

- **Electricity prices** | the higher, the more costly it is to run the electrolyser.

- **Natural gas prices** | the lower, the worse the business case for green hydrogen as opposed to hydrogen produced with natural gas.

- **Green hydrogen prices** | the lower, the more attractive green hydrogen becomes compared to blue or grey hydrogen. But at the same time, it worsens the business case for the green hydrogen producer. Prices for blue or grey hydrogen are influenced by input fuel costs, CO2 taxation/ storage costs etc.

- **Side products** | ability to sell side products such as excess heat from electrolysis to a district heating network or large industrial customers.

Furthermore, there is a significant gap between the electrolysis systems produced and supplied today and the requirements for a green hydrogen facility which is capable of supplying GW's equivalent of hydrogen and fulfilling the system integration role while rolling out GW's of offshore wind. The challenges refer among others to:

- Technical challenges of designing stacks and systems appropriate for this scale;

- Engineering, procurement and construction capabilities to realise industrial standard plants;

- The ability to produce stacks and key balance-of-plant components in a rate allowing the realisation of GW-scale capacity per annum;

- The capacity of the supply chain for the electrolyser manufacturer to scale-up rapidly;

- The reduction in production cost for electrolysers to a point where green hydrogen becomes cost competitive with fossil fuels.

23 Chehade, Mansilla, Lucchese, Hilliard, & Proost: Review and analysis of demonstration projects on power-to-X pathways in the world, International Journal of Hydrogen Energy, 2019.(link)
24 Van Schot & Jepma: North Sea Energy - a vision on hydrogen potential from the North Sea, 2020. (link)
25 Van Schot & Jepma: North Sea Energy - a vision on hydrogen potential from the North Sea, 2020.(link)

However, the economic factors are expected to change favourably for electrolysis, especially influenced by the CO2 taxations and a decrease in the capital investment costs (CAPEX) for electrolysers. When conducting an expert elicitation study, it was found that by 2030, R&D funding can reduce capital costs for different electrolysis technologies by 0 – 24% and scale-up of production alone by 17 – 30%.[26] Combined, there is a huge reduction potential for CAPEX figures for electrolysis by 2030.

In order to reach GW scale electrolysers in 2030, upscaling towards projects of 100-500 MW in the coming period will be essential to drive costs down and realize production benefits for the electrolyser systems. According to a report from IRENA, electrolyser producers are upscaling and anticipating further cost declines. In the same study learning rates of around 16-21% for electrolysers are given, based on a meta-analysis and it is also mentioned that a cost reduction of over 40% may be achievable by 2030.[27] However, in order to reach these estimates, incentives for constructing and upscaling of electrolysers by providing financial instruments to actually implement the existing roadmaps is desirable.

As mentioned above, scale up of current electrolysis capacity from MW to GW scale in 2030 is necessary to realize an efficient energy system. Therefore, further technology development is required, which should lead to a cost reduction of green hydrogen of a factor 3 to 4.[28] This means that:

1. R&D including pilot and demonstration projects should be financially stimulated via subsidy schemes;

2. During the scale up phase (2023-2030) electrolysis requires public support schemes to reach a viable business case and promote the development of an efficient energy system with net socio-economic benefits.

Here, the cost reduction of offshore wind is an example of the pathway green hydrogen production could follow. The capital cost of a wind turbine has declined significantly between 2010-2020. This resulted in awarding offshore wind parks without subsidies.

[26] Schmidt, Gambhir, Staffell, Hawkes, Nelson & Few: Future cost and performance of water electrolysis - an expert elicitation study, International Journal of Hydrogen Energy, 2017.(link)
[27] International Renewable Energy Agency: Green hydrogen cost reduction scaling up electrolysers to meet the 1.5°C climate goal, 2020.(link)
[28] Institute for Sustainable Process Technology: Final report ISPT GW water electrolysis project integration in five industrial clusters, 2020. (link)

5.4. Operation and dispatch

The operation of an electrolyser will mainly depend on the price spread between on the one hand the price of electricity including transport tariffs and taxes, and on the other hand the price of hydrogen including transport tariffs, taxes and storage costs. If the marginal cost is lower than the sales price of hydrogen, then the electrolyser will operate. From a climate perspective, it is important to ensure that the electrolyser only operates on green electricity. Producing hydrogen via an electrolyser operating on the current electricity mix (to a large degree based on fossil fuels) might potentially lead to more greenhouse gas (GHG) emissions than the conventional hydrogen from fossil fuels. For example, hydrogen production based on the current German electricity mix would emit two times more GHG emissions than conventional hydrogen production from fossil fuels, and more than 25 times that of hydrogen produced completely with renewable electricity.[29]

Thus, if the incentives for operating the electrolyser do not take GHG-emissions into account, more GHG-emissions might be emitted by the electrolysis solution than by the conventional fossil-based solution. This might especially be the case if the market optimized operation of the electrolyser results in close to full operation in all hours of the year regardless of the GHG emission related to the electricity used. Therefore, it is important to analyse the impact of dispatch incentives on different players in the market, including renewable energy developers and incentivize efficient dispatch, i.e. the short-term determination of the optimal utilization of energy system assets in order to meet the system demands. This could be done through e.g. higher CO2-pricing or location and time-specific Guarantees of Origin (GoOs). In the follow-up paper on the regulatory framework for hydrogen, more consideration is given to GoOs.

As mentioned above, the optimal hours of operating an electrolyser will depend on the price of electricity and of hydrogen. From an integration of large-scale offshore wind point of view, the merit order of most offshore wind farms with a grid connection will be to deliver i) to the electricity grid and ii) in times of higher production than the grid capacity, the offshore wind farm will deliver its' excess supply of electricity to the electrolyser. Therefore, the estimated hours of operation of an electrolyser are roughly between 2200 and 3500 hours, some for more hours.[30] This all depends on the build out level of renewables and the availability of hydrogen infrastructure, storage, and flexible hydrogen consumption. For dedicated green hydrogen production, i.e. hydrogen production from renewable energy that is not grid connected, the optimal hours of operation will be higher as this is directly linked to the amount of renewable energy hours. The exact number will depend on the harvesting technology (e.g. wind turbines or PV-panels) and the location of these.

At present, the operation of electrolysers is only commercially viable for a very few applications, but this is expected to change as the investment costs for electrolysers decrease and more renewable energy is added to our energy systems.

[29] European Commission: Hydrogen generation in Europe - overview of costs and key benefits, 2020. (link)
[30] Navigant: Integration routes North Sea offshore wind 2050, 2020.(link)

7 Conclusion

The European Union aims for climate neutrality i.e. net zero greenhouse gas emissions in 2050. In order to reach that objective, the offshore renewable energy strategy of the European Commission projects around 300GW of offshore wind.[31] The deployment and integration of such vast amounts of offshore wind in the energy system, with maximum socio-economic benefit, requires large-scale flexible electricity consumers (i.e. usage by final consumers, but also conversion and storage).

Large-scale flexible electricity consumption will

1. reduce the cost of grid reinforcements;
2. support the economic viability of intermittent renewable energy deployment;
3. increase the share of intermittent renewable electricity capacity;
4. enable additional build out of offshore wind, which supports more electrification while enabling decarbonization of hard-to-abate sectors;
5. reduce curtailment of offshore wind, and;
6. function as seasonal storage.

Furthermore, import of green hydrogen into the EU from surrounding countries is expected. Its extent will be based on cost reductions and will be subject to market dynamics and pricing.

Highlight
Large-scale flexible electricity consumption has important societal, environmental and financial benefits.

In this paper, the consortium came up with four guiding principles for the integration of large scale intermittent renewable energy in the energy system:

1. A timely development of a hydrogen market and infrastructure (both within and between regional, industrial clusters);
2. Mechanisms which provide incentives for efficient locations for electrolysis from an energy infrastructure perspective;
3. Mechanisms which support timely construction and upscaling of electrolysers by e.g. providing investment certainty allowing to kick start large scale flexible consumption;
4. Market and regulatory mechanisms which provide dispatch incentives to improve optimal usage of renewable energy and infrastructure.

[31] European Commission: An EU strategy to harness the potential of offshore renewable energy for a climate neutral future, 2020.(link)

This paper provided an energy system perspective on the integration of intermittent renewable energy and the need for large-scale flexible electricity consumption. The aim of the follow-up paper is an analysis of possible market designs and regulatory frameworks for electrolysis in order to realize an optimal deployment of renewable energy and the energy system.

8 Appendix

Appendix A: Offshore wind projections

In this appendix, an overview of the current offshore wind energy targets is shown, see Table 1.

Table 1: Offshore wind targets for the North Sea.

Country	2030	After 2030
Netherlands	11,5 GW[32]	Looking for 20-40 GW additional OSW development areas as well as ~6 GW additional capacities before 2030
Germany	20 GW	40 GW
Denmark	5,5 GW	10,5 GW
United Kingdom	40 GW	
North Sea Basin	77 GW	180 GW for North Sea region

Table 1 Offshore wind targets. Danish projections based on national Analysis Assumptions.[33]

Appendix B: National hydrogen strategies

Based on different sources the following electrolysis capacities are indicated or agreed upon in National Climate Related transition plans, see Table 2.

Table 2: PtX capacity plans.

Country	2030	After 2030
Netherlands	3-4 GW[34]	Agreed in the Climate Agreement to be realized in 2026-2030 for electrolysers. Mentions other PtX technologies without specific figures
Germany	5 GW	Based on Hydrogen Strategy BMWi. Additional 5 GW in 2035
Denmark	N/A	PtX strategy expected in Q3 2021
United Kingdom	5 GW	
European Union	40 GW*	180 GW for North Sea region

Table 2 Electrolysis capacity expansion plans. Numbers for Denmark are not currently known and numbers for the United Kingdom are preliminary.
*In its' 2X40 GW Green Hydrogen Initiative, Hydrogen Europe proposes to supplement the 40 GW of electrolysis capacity in the EU, with another 40 GW in Ukraine and the North African countries which could then be transported to the EU.

32 The government of the Netherlands: Climate agreement, 2019.(link) The Ministry of Economic Affairs: Letter to Parliament on offshore wind energy roadmap 2030, 2020.(link)
33 Energistyrelsen: Analyseforudsætninger til Energinet 2020 – Vindmøller på havet, 2020.(link)
34 The government of the Netherlands: Climate agreement, 2019.(link)