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Renewable Energy for Industry: Offshore Wind in Northern Europe

This note expands on the findings of a recent IEA Insight Paper on renewable energy for industry, exploring further the potential for decarbonising the European industry by replacing fossil fuels with electricity from offshore wind in Northern Europe, either directly or via hydrogen production.

Replacing fossil fuels as energy sources, feedstocks and process agents in the European industry would require large amounts of clean electricity. The technical potential for renewable electricity production from offshore wind appears indeed large in Northern Europe. The potential for profitable substitution is significant when electric technologies allow for large energy savings. A broader substitution may require high carbon prices, and in some cases may have to go through the production of hydrogen. However, green hydrogen may also be produced from fossil fuels with carbon capture, possibly at lower costs than from electrolysis run on offshore wind power. And storable and transportable chemicals and fuels may be imported from areas with better renewable resources at lower costs.

Nevertheless, reduced energy dependence from fossil fuel imports, and reduced price volatility of inputs essential to industry may justify an expansion of offshore wind capacities to specifically contribute to the decarbonisation of European industries.

Introduction

Offshore wind power, alone or in combination with other renewable energy sources, could be deployed in European seas to specifically respond to the needs of the European industry for energy, process agents and feedstocks in replacement of fossil fuels. This would come on top of its likely contribution to responding to current and forthcoming usual electricity needs.

The present note aims at responding to the following questions:

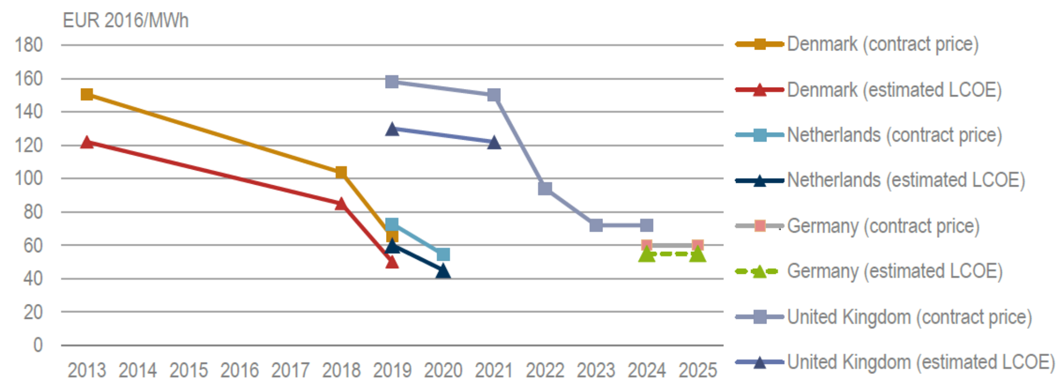
- What is the potential for offshore wind in Northern Europe and at what costs?
- Which industrial productions in Europe could be decarbonised if large amounts of green electricity were available?
- Which current and future uses of hydrogen, ammonia and other hydrogen-rich chemicals could be produced with green electricity to reduce carbon footprint?
- How do green electrification options compare with other options for decarbonisation?

Offshore wind power potential in Northern Europe

Offshore wind power is an industrial reality today with over 18 GW installed by end 2017, of which over 16 GW in Europe. It is expected to increase by 22 GW over 2018-2022, of which 14 GW in Europe. The last two years announced spectacular cost reductions in the Netherlands, Denmark, Germany and the United Kingdom, through tender results for turbines to be commissioned in the next five years. Increasing competition, technology improvements and lower financing costs combine to explain this trend. Generation costs for future bottom-fixed plants can be estimated in the range of EUR 55 to 70/MWh, to the extent recent auction results can be used as a guide (Figure 1).

The potential of offshore wind in Northern Europe was recently estimated by WindEurope (2017). According to that study, the gross resource potential from five nautical miles from the shore to the limit of the Economic Exclusive Zones of EU member States (including the United Kingdom) exceeds 10 terawatts (TW) and 50 000 TWh/y in three key basins (Atlantic, North Sea and Baltic).

Figure 1: Offshore wind auction results and LCOEs by expected commissioning date



Source: IEA, 2017a, *Renewables 2017.* Notes: UK projects include all transmission costs, which usually account for about 10-15% of total generation costs; in other countries, national transmission system operators are responsible for building the offshore and onshore transmission infrastructure; LCOE estimates for bids in Germany are based on the Gode Wind project bid price as other projects will receive whole electricity price.

A smaller technical potential of 12 000 TWh is defined by excluding a number of areas: shipping lanes, environmental protection, dumped munitions, average wind speeds below 7.5 or 8 m/s at 100 m above mean sea level, water depth greater than 1 000 m in the North Sea and Atlantic, or greater than 70 m in the Baltic due to ice risks for floating offshore. The density of wind turbines is reduced to facilitate shipping, wind speed recovery and micro-siting to avoid existing infrastructures (cables, pipelines) and special conservation interests.

Table 1: Offshore wind potential in Northern Europe

Volumes in TWh/y	Equivalence to EU demand	Capacity (GW)	Average marginal cost, €/MWh
810	25%	197	54
1 620	50%	394	60
3 240	100%	788	64
6 480	200%	1 576	69

Source: WindEurope (2017), *Unleashing Europe's offshore wind potential.*

WindEurope defines offshore wind as "economically attractive" up to a cost of € 65/MWh (including transmission to shores), and defines an economic potential of 600 to 1 350 GW generating 2 500 to

6 000 TWh/y, with expected capacity factors of about 47%. Fully achieving such potentials would require the installation of 46 000 13-MW turbines to 90 000 15-MW turbines.

Earlier studies often had more restrictive assumptions regarding the size of turbines, the maximum depth of seawaters, or the environmental constraints, leading to lower estimated potentials. For example, EEA (2009) suggested a gross potential of 30 000 TWh, a technical potential of 3 500 TWh by 2030 and an economic potential of 2 600 TWh. This remains, however, very significant compared to the current total generation of electricity in the European Union, of 3 200 TWh in 2015.

These potentials largely exceed any deployment based on currently-projected electricity demand. In the *World Energy Outlook's* New Policies Scenario (NPS), offshore wind capacity reaches 160 GW by 2040, vs. 350 GW in the Sustainable Development Scenario (SDS) (IEA, 2017b). Generation from offshore wind reaches 580 TWh/y in the NPS and more than 1 200 TWh/y in the SDS. This only represents 3.5% of overall generation in the SDS at global scale, but may reach or even exceed 10% in Europe, depending among others on a cost effective integration of variable renewable power and of a possible expansion of demand (IEA 2018).

One can thus assume that a significant potential of electricity remains available to further decarbonise the European industry if specific strategies and policies were implemented. This would represent hundreds of GW that could generate thousands of TWh – beyond the electricity demand that currently figures in climate-friendly scenarios, notably in generating hydrogen from electrolysis of water.

Figure 2: Wind farm areas defining an economic potential up to € 65/MWh under the baseline and upside scenarios

Source: WindEurope (2017), *Unleashing Europe's offshore wind potential.*

While its environmental benefits would be obvious in terms of reduced reliance on fossil fuels, improved air quality and mitigation of climate change, such a deployment could also have some negative environmental impacts, which would need to be mitigated. Much of the possible impacts relate to biodiversity through direct conflict (e.g. collisions, loss of habitat, smothering, etc.) or indirect impacts (increased effort for feeding, avoidance behaviour, etc.). Closer to shore, biodiversity impacts can be compounded by impacts to people. For a review of issues of concerns and proposed mitigation measures, see Ecofys and RPS (2017).

In the remainder of this note, options are considered to further decarbonise the European economy in using wind power above and beyond the shares that are usually considered to respond to the foreseeable power demand of the EU.

Power markets vs. dedicated investments

The offshore wind potential in Northern Europe may provide large amounts of green electricity at reasonable costs in the medium and long term. Assuming that onshore wind power deployment would face increased acceptability issues beyond providing over 20% of current EU electricity demand (SDS, IEA 2017b), one might consider four alternative or complementary options to provide additional low-carbon electricity:

- a large fleet of new-built nuclear power plants; however, to prove competitive with wind power the nuclear option would have to demonstrate sharp cost reductions from the level reached in the United Kingdom, and/or the higher capacity factor of nuclear to prove a determinant advantage.
- a large fleet of new-built coal plants with carbon capture; this option may have some traction in some European countries; however, in most case it would be more efficient to develop carbon capture of direct fuel use in the industrial plants, than to replace fossil fuels with electricity produced with fossil fuels with capture in power plants.
- a larger deployment of solar photovoltaic power in the South of Europe; however, its lower capacity factor may prove more problematic for industrial uses than is the case with offshore wind power, unless electricity storage is deployed at very low costs;
- a large development of solar and wind power imports from North Africa.

Without excluding significant contributions from these options, notably the two last ones, offshore wind power thus appears the most likely candidate to support a possible increase of green electricity demand to support the decarbonisation of industry.

Although some capacities may be dedicated to specific industrial facilities, most offshore wind power in Northern Europe may be integrated in the European power markets. As the share of variable renewables will increase in Europe, electricity prices will likely see important variations depending on the supply – demand balance.[1] Despite integration efforts, from time to time limited amounts of "surplus" electricity might be available at low costs, allowing for a limited additional electrification of industry.

[1] Wind regimes are often somewhat correlated across Europe. A simulation of an onshore wind fleet of 280 GW of installed capacity, well distributed across the European system, showed that in winter the daily average power generation from wind varies between 40 and 170 GW depending on wind conditions (Burtin and Silva, 2015).

However, if offshore wind power is to represent a high share of future electricity supply due to further electrification of industry, its estimated costs remain relevant. Sufficient investments in both electricity-consuming industrial capacities, and electricity-producing capacities, would be mainly dependent on each other. If this is the case, for investment to take place average prices would need to reflect the underlying costs, whatever forms the exchange of electricity takes (e.g. wholesale markets, power purchase agreements).

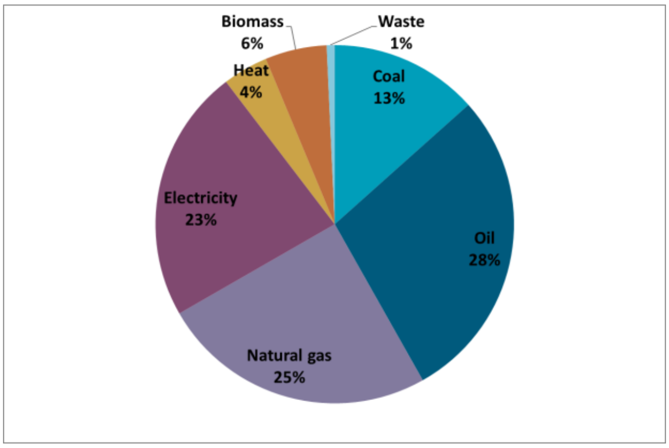
The European industry demand

In the EU statistics, industry is the second most energy consuming sector in the EU with 25% next to transport (33%), equal to households (25%), ahead of services (14%) and agriculture & forestry (2%). However, the energy consumption taken in account in this oft-quoted break-down, of 275 million tonnes oil-equivalent (Mtoe), or 11.5 exajoules (EJ), does not account for the 97 Mtoe (4 EJ) of fossil fuels consumed as feedstock, termed "non-energy consumption" in the energy statistics of the EU. This use of fossils, mostly petroleum products (84.5%) and natural gas (NG) (16.3%) is particularly important in the chemical industry. Most of the remainder of fossil fuels, and part of the electricity, is used to produce process heat and/or steam within industrial facilities. Figure 3 below reveals the importance of fossil fuels, and primarily oil and gas, in the overall final energy consumption of the EU industry when all uses are taken in account.

Expressed in terawatt hours, the annual energy and non-energy uses of fossil fuels in the European industry thus totals about 4 330 TWh of final energy demand. Of course, decarbonisation of the industry in the EU will also rest on energy efficiency improvements, material efficiency, carbon capture and a partial shift towards biomass-based fuels and feedstocks (IEA, 2017c). Still, these numbers suggest that if electricity were to massively replace fossil fuels, additional demand may also be in the thousands of TWh, i.e. be of the same rough order of magnitude than the current electricity consumption of the entire EU, of about 3 250 TWh.

Three industries are responsible for the bulk of industrial CO_2 emissions – cement, chemicals and iron and steel. In these sectors, CO_2 emissions originate from processes as well as from combustion for energy purposes. It is worth looking at these sub-sectors in some more details, after consideration of the more general case of replacing fossil fuels with electricity for generating heat and steam.

Figure 3: Sources of final energy consumption in the EU industry in 2014 for energy and non-energy uses.



Source: IEA 2017c, *Energy Technology Perspectives.*

Heat and steam

In the NPS, import NG prices in Europe, driven by liquefied NG (LNG) imports from the USA, grow to USD 7.9/MBtu by 2025 and USD 9.6/MBtu by 2040 (IEA, 2017b), that is, € 22 to € 27 per MWh – significantly lower than the foreseeable cost of offshore wind power.

Electricity can be considered for substitution on the ground of greater efficiency making for the gap in energy costs. EPRI (2018) provides a number of examples relying on infrared heating, ultraviolet curing, microwave and radio frequency heating, induction heating, melting or hardening, and electric arc furnace, in sectors as diverse as chemicals and petrochemical, iron and steel, food, drink and tobacco, glass, pottery and building materials, machinery, paper and printing. It sees a technical potential of 250 TWh in Europe (EU+5), and a smaller economic potential (with payback time less than three years, not accounting for CO_2 reduction or any process quality improvement) of 178 TWh, which would substitute to 43 Mtoe of natural gas, equivalent to 500 TWh. This represents 11.5% of the overall fossil fuel consumption of the EU's industry. These figures clearly reveal the (final) energy efficiency improvement involved.

Another area could be that of equipment with high coefficient of performance (COP) recycling energy waste fluxes, such as mechanical vapour recompression machines, with COP ranging from 5 to 10 as they avoid the condensation losses of low-temperature low-pressure steam, or heat pumps with COP from 2 to 4, depending on the temperature lift that is necessary. Voltachem (2016) assume a potential for these technologies to halve energy for the heat demand of EU's chemical industry below 200°C and save 15% to 20% in total.

One may also consider cheap equipment called to work only when market electricity prices are lower than average (at times of "excess" supply), such as electric resistances immerged in fossil-fuelled boilers. Some large industries already operate steam generation in electric boilers replacing NG-fired boilers as a demand-side management tool using low-cost variable renewable power.

Another dimension to consider is that electrification of industry can provide flexibility services to power grids confronted with the challenge of integrating large shares of variable. For example, Trimet Aluminium SE retrofitted its factory in Essen to allow managing the heat and keeping the temperature of smelters in a safe range despite fluctuating amounts of electricity.

A fuller replacement of fossil fuels with renewable electricity may however require carbon prices reaching high levels[2] of about € 120 to 150/t CO_2 – somewhat more than assumed by 2040 in IEA's Sustainable Development Scenario (IEA 2017b). But is it technically possible in all industrial sectors? Chemicals, iron and steel, and cement, characterised by large process emissions, need to be considered more closely.

Chemicals

The production of chemicals may offer a considerable potential for electrification. The DECHEMA study (2017) for the European Council of Chemical Industry shows that an ambitious scenario could

[2] Based on the assumption that the combustion of natural gas entails emissions of 238 g CO_2/kWh low heating value, taking in account combustion and upstream exploitation emissions. A carbon tax of € 120/t CO_2 would thus raise the total cost of natural gas as a source of heat to € 50 to € 63/ MWh. Note that for hydrogen from electrolysis to be competitive with natural gas, the carbon price would need to be higher at about € 230/t CO_2.

save 101 Mt CO_2, or 84% of the anticipated emissions of the European chemical industry. The main share of emission cuts would come from using hydrogen from low-carbon electricity to produce ammonia and methanol, olefins (ethylene and propylene), and benzene, toluene and xylene (BTX). This would require 1 900 TWh of green power according to the "ambitious scenario" of the study, and up to 4 900 TWh in a "Maximum scenario".

Hydrogen, ammonia and methanol

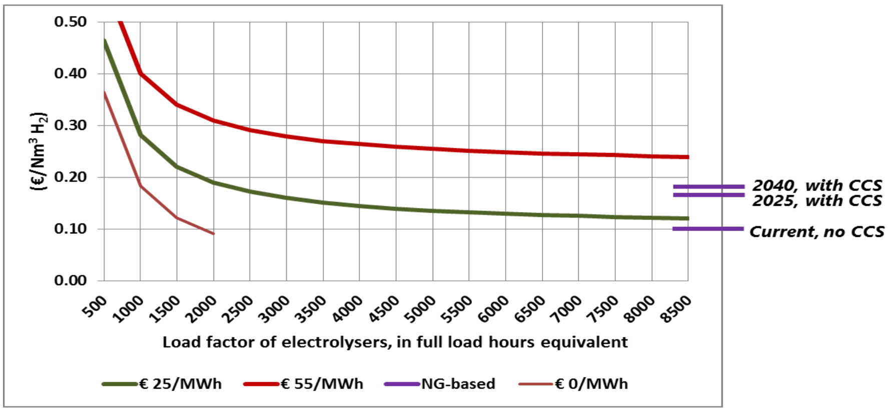
The total production of **hydrogen** today is of 9 million tonnes per year (Mt/y) in Europe. Half is used in refineries to reduce the sulphur content of fuels, 40% goes to ammonia production, and the rest is used for other chemicals, and metallurgy.

Over 95% of hydrogen is currently produced from fossil fuels: steam methane reforming (SMR), naphtha partial oxidation and coal gasification. This production entails important CO_2 emissions, from 9 to 12 t CO_2/t H_2. Assuming NG price of € 5.7/MBtu in Europe, the cost of producing hydrogen can be assessed at € 0.114/Nm^3. Capturing and storing 90% of the CO_2 in the flue gas of SMR plants non-integrated in a broader industrial complex ("merchant" plants) would requires an increase of almost 80% of the total plant costs, and present a CO_2 avoidance cost of € 60-70/t CO_2[3]. The levelised cost of hydrogen would increase to € 0.165/Nm^3.

These costs are particularly contingent on the cost of natural gas, set to progressively increase over time (IEA 2017b). Hydrogen from an SMR merchant plant with CCS would thus cost about € 0.18/Nm^3 in 2025 and € 0.22/Nm^3 in 2040.

Figure 4 shows the cost of hydrogen from water electrolysis with respect to the load factor of electrolysers, in comparison with that of NG-based hydrogen. Two electricity prices are figured: € 55/MWh which could be the average cost for the first hundreds of TWh from offshore wind, and € 25/MWh (~USD 30/MWh), which could represent the cost for hybrid solar PV and onshore wind power in World's best resource areas, under a set of rather positive assumptions relative in particular to financing costs (IEA 2017a and b).

Figure 4: Cost of hydrogen from water electrolysis for various electricity prices and electrolysers load factors

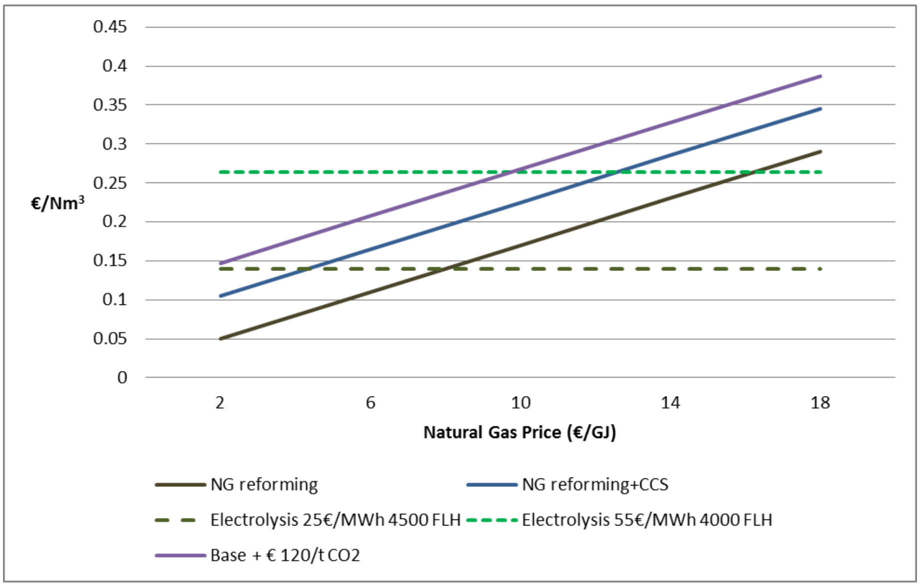


Assumptions: Electrolysers Capex USD 450/kW_{input} (Simonsen, 2017), + installation 30%, + maintenance 20%, efficiency 70%, WACC 7%, lifetime 30 years. Gas prices in Europe: Sustainable Development Scenario, IEA 2017b, *World Energy Outlook*.

[3] The cost of CO_2 transport and storage is assumed to be € 10/t CO_2, the difference is the cost of capture according to IEA GHG 2017a.

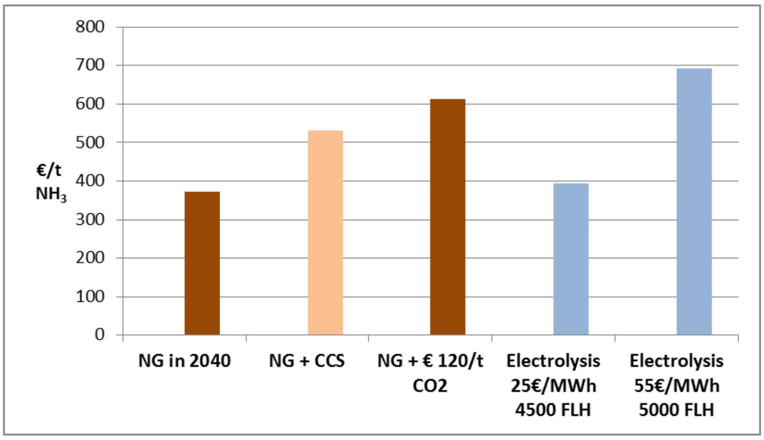
At the 47% load factor considered for offshore wind power, the cost of large-scale electric hydrogen production would be € 0.263/Nm^3, over twice the current cost of producing hydrogen from SMR without carbon capture. As NG prices progressively increase in Europe, and carbon emission reductions across the entire economy become necessary to comply with the EU commitments, the cost gap with offshore wind-based hydrogen would progressively reduce but probably not enough to fill the cost gap with CCS if widely available (Figure 5).

Figure 5: Cost of hydrogen from natural gas vs. from electrolysis



Ammonia (NH_3) is at the heart of the fertiliser industry, bringing nitrogen to the plants. It is also used to manufacture explosive, cleansers, dyes, fibres, plastics, nylon and acrylics, or as a refrigerant. The production of ammonia from wind power, first experienced in the late XIX Century by the Danish scientist Poul la Cour, continues to be investigated and developed (Morgan, 2013; Nayak-Luke, Bañares-Alcántara and Wilkinson, 2017). Ammonia can be produced from water electrolysis and nitrogen taken from the air with the well-established Haber-Bosch (H.-B.) process at costs that largely depends on the cost of electricity, provided the electrolysers have load factors above one third, and the ammonia synthesis loop is run continuously.

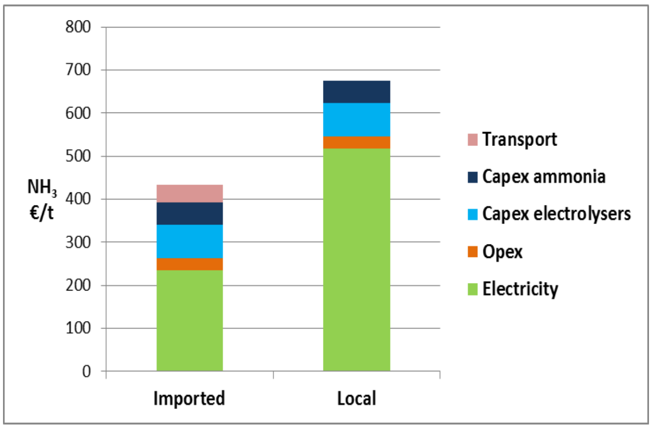
Figure 6: Costs of ammonia from natural gas in Europe, vs. from electrolysis



In the case of hydrogen production in integrated ammonia/urea plant or a methanol plant, where the CO_2 generated from the process is often captured and reused, the cost of capturing the remaining, more diluted, CO_2 emissions is higher than in the case of merchant plants and reaches € 80 to € 100/t CO_2 (IEAGHG 2017b). This, and the simplifications of the H.-B. process permitted by the greater purity of renewable electricity based relative to NG-based hydrogen, can slightly improve the competitive position of electric ammonia produced from offshore wind in Europe vis-à-vis natural gas but still does not fills the gap, as shown on Figure 6 (based on natural gas cost expectations in the SDS, of € 6.66/Mbtu in Europe by 2040).

More importantly perhaps, ammonia production does not require other material inputs than air and water, and transport of ammonia in oceangoing tanker and pipelines is already routine, at a cost of about 40 €/t over long distances. Therefore, as shown on Figure 7, an even more serious competitor for offshore-wind based ammonia production might be solar and wind-based ammonia imported from areas with much better resources, such as North-Africa, (Philibert, 2017a and b). Over such short distance however, imports of electricity via submarine cables could play a relatively similar role.

Figure 7: Costs of European electric ammonia production vs. imports from best resource areas



Box 1: offshore hydrogen or ammonia?

Some studies have been conducted recently to assess the possible advantage of converting offshore wind power into hydrogen on existing oil and gas offshore platforms close to be decommissioned (e.g. Jepma and van Schot, 2017). The concept would save investment in electric grid connection while extending the use of current oil and gas pipes to carry hydrogen on shores. However, these possible advantages do not clearly balance out the inconvenience of installing and running large-scale electrolysers offshore, and modifying the grid infrastructure. Pipes would need serious modifications to carry pure hydrogen. To transport ammonia, another option requiring more offshore installation, compressors would need to be replaced with pumps. An easier option would be to mix some hydrogen into NG fluxes but it appears limited in scope, and would not do much to prolong the use of NG grids.

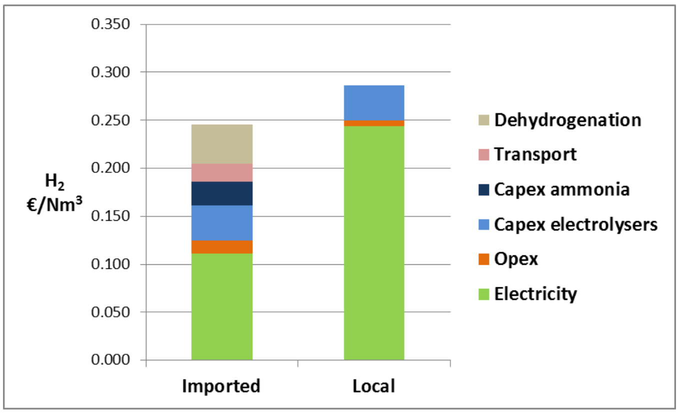
Methanol, the simplest alcohol, is widely used as a precursor of plastics (through both propylene and formaldehyde), plywood, paints, explosives and permanent-press textiles. It is also used to form gasoline additives in some countries, enters the production of fatty acid methyl ester biodiesel, and forms the basis of dimethyl ether (DME), an aerosol spray propellant and a transportation diesel fuel. DME can also be used in combination with liquefied petroleum gas for home heating and cooking. 60% of methanol is used as a feedstock, while 40% enters into energy fuels. The global production of methanol reaches around 80 Mt/y, and its European demand accounts for about 9 Mt/y.

Methanol (MeOH) is usually produced from fossil fuels through catalytic reactions to associate carbon monoxide and hydrogen. Alternatives include biomethanol, and the hydrogenation of CO_2 with renewables-based hydrogen, demonstrated in particular by Carbon Recycling International (Stefansson, 2017). Even if the CO_2 is of fossil origin, there will be benefits of capturing and recycling it to replace additional fossil fuel or feedstock. DECHEMA (2017) assesses them at over 1.5 t CO_2 per t MeOH. In the long run however, as the global economy nears the net zero emissions level necessary to stabilise the atmospheric greenhouse gas concentrations, carbon recycled in synthetic fuels and goods will have to come from the air, via photosynthesis or direct air capture

For green methanol like for green ammonia, the competition to offshore wind power in Northern Europe may come from areas with better and cheaper renewable potential, with reduced shipping costs as methanol is liquid at normal temperature and pressure, provided CO_2 can be procured.

However, for applications requiring pure hydrogen, the total cost of turning hydrogen to ammonia, transport it and extract pure hydrogen from ammonia would considerably reduce the competitive edge of producing ammonia in remote regions with better resources, as shown on Figure 8. This might be especially relevant for refineries and iron and steel.

Figure 8: Costs of European hydrogen production from renewables vs. imports of hydrogen as ammonia from best resources areas



Other chemicals

While the efficiency in the electric production of ammonia and methanol is roughly comparable with the efficiency of producing them from fossil fuels, the electric production of olefins is 40% more energy intensive than naphtha cracking, according to DECHEMA (2017). The electrification of olefins and BTX production thus largely explain the high electric demand of a complete transformation of the European chemical industry. Nevertheless, such electric paths could be carbon sinks for other industrial sectors, requiring large amounts of CO_2 captured from power or industrial plants or directly from the air, as a source of carbon feedstock.

Iron and steel

Steelmaking is a considerable challenge as it represents 4% of Europe's total CO_2 emissions. Emissions originate from both energy use and reduction of iron ore. Among other options for decarbonisation of steelmaking such as HIsarna, (IEA 2017c), renewable electricity could be used either directly through electrolysis of iron ore, also known as electro-winning. Two processes have been developed at lab scale, as part of the European research programme Ulcos, or Ultra-Low Carbon Dioxide Steelmaking. Under Ulcowin, iron ore would be electrolysed at a "room temperature" of about 110°C. Under Ulcolysis, iron ore would be solved or suspended in an acid or alkaline solution, or melted in a saline solution for high temperature electrolysis around 1 600°C. The Siderwin project of Arcelor Mittal is a continuation that includes demand-side management of variable renewables (Birat, 2017). Meanwhile, start-ups attempt develop innovative processes and materials for molten iron oxide electrolysis (Sadoway, 2017).

Another option for a greater uptake of electricity in steel making is to use hydrogen to reduce iron ore in the direct reduction path, which includes electric arc furnaces. It is being developed by the Hybrit project, as well as others (Görnerup, 2017; Birat, 2017). This option seems to present a higher technical readiness level, and allows for progressive introduction in existing direct iron reduction facilities. However, it is less efficient than direct electrification. If regional offshore wind power is to be the main source of electricity for steelmaking, direct electrification may thus become the best choice. At 2.6 MWh of electricity per tonne of crude steel (Weigel et al., 2016), conversion of the European steelmaking industry would require some 416 TWh for 160 Mt steel per year.

Cement

The calcination of limestone to produce lime, first step of cement-making, based on burning fossil fuels, as well as biomass and waste, is an energy-intensive process. As the reaction progresses, the material cools itself, making heat transfers to unreacted limestone increasingly difficult. New microwave-assist-technology (MAT) combines radiant heat and microwave activation in the same electric kiln to dissociate $CaCO_3$ to CaO simultaneously at the centre and the surface of the material, increasing the rate and uniformity of calcination (Fall et al., 2011).

For the cement industry, besides such options for efficient partial electrification, options for also reducing process emissions are still under laboratory development and not further examined in this note (see Philibert, 2017b; IEA/CSI, 2018). However, CO_2 captured from cement production could be recycled into chemicals and fuels with renewable-based hydrogen, as considered above.

Applications in the power sector

Besides its direct but variable contribution to generating electricity in the EU power grids, offshore wind power could be used to produce hydrogen, which would most likely be turned into more easily storable products. These could then be burned in balancing thermal power plants providing electricity when the sun does not shine, the winds do not blow and other options (e.g. storage, demand side response) are exhausted. The preferred candidate to this function is ammonia. Nuon is currently converting the three 437-MW Magnum combined cycle gas turbines at Eemshaven (The Netherlands) to run on hydrogen, then ammonia. Other options include synthetic methane and liquid hydrocarbons.

To produce electricity from ammonia, about three times more primary electricity would be required, the combination of 70% electrolysis efficiency and 50% heat to electricity conversion resulting in 35% round-trip efficiency (Grinberg Dana et al)[4]. If, for example, the need for firm power from flexible thermal plants were in Europe of 10% of the total consumption, or 325 TWh, the need for primary electricity would be up to 930 TWh. Electricity from renewable ammonia would cost at least three

[4] Some studies, e.g. Wang et al. 2017, suggest that higher round-trip efficiencies are possible with ammonia storage thanks to full integration of electrolysis and generation based on reversible solid oxide fuel cells.

times more than the cost of electricity to produce it, not even accounting for the cost of long term storage[5] and that of the peaking plants that would turn the fuel into power. If the electricity primarily comes from offshore wind power at € 55/MWh, that cost would thus be € 165/MWh.

Therefore, utilities might prefer to procure carbon-free ammonia from regions with significantly lower renewable electricity costs thanks to better solar and wind resources. If the original power costs € 20/MWh, the cost of electricity from ammonia will be close to € 60/MWh. At € 40/t for long distances, while a tonne of ammonia has a low heating value of over 5 MWh, the cost of shipping ammonia would not likely modify this preference, as shown on Figure 7.

The transport sector

Hydrogen as a transport fuel is attracting much attention, but difficulties persist and deployment has remained slow to date. Japan, probably the country whose industry is most engaged in developing fuel cell vehicles (FC), targets 800 000 FCVs by 2030, requiring about 80 000 tonnes hydrogen per year. Even if Europe was to set up similarly ambitious targets for herself, weighted by population, this would require about 15 TWh and not form a very large outlet for offshore wind power.

Meanwhile, electric transportation is making remarkable progress for light duty vehicles, but some transport modes seem difficult to electrify in full, in particular long-haul trucking, marine transport, and aviation. In this respect, one should consider possible use of green electricity to manufacture transport fuels[6]. Some could be without carbon, such as ammonia. It seems relatively well fitted for ships as recently acknowledged by Llyod's Register and the University of Maritime Advisory Services (2017), but more difficult to generalise on land or in the sky. Combining recycled carbon and green hydrogen would allow producing synthetic, renewable and carbon-neutral hydrocarbons of any type – now tagged as "electrofuels" – either from methanol or more directly from carbon monoxide and hydrogen through Fischer-Tropsch fuel synthesis, as proves Sunfire in Dresde – on the small scale of one barrel of synthetic diesel per day (DECHEMA 2017).

Here again, in a world full of a considerable number of fossil CO_2-emitting source, the origin of the carbon first captured does not matter much. But it will need to be taken out of the atmosphere in the longer run, or be compensated in full with negative emissions.

The overall efficiency from electricity to energy used in transport would be small, assessed as 13% overall (including the efficiency of internal combustion engines) versus 73% for electric traction (Malins 2017). Costs would likely by high but estimates diverge, from twice the cost of conventional fuels according to Sunfire quoted by DECHEMA, to six times that of diesel or jet fuel according to Malins, although based on a cost of € 50/MWh. However, the cost of synthetic fuels may decline considerably over time and, according to Frontier Economics (2018), and approach that of fossil fuels.

In any case, the cost of electricity dominates the cost of electrofuels, so that procurement from regions with significantly lower renewable electricity costs would likely be a must, as these "oil products" are routinely shipped long distances.

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[5] In case of ammonia, this cost is similar to that of liquefied petroleum gas storage. The cost of storing cryogenic hydrogen over half a year would be almost 30 times greater than storing ammonia over the same time length, according to Bartels (2008).

[6] This would also apply to heating fuels complementing electrification and more specific solutions in buildings and industry.

On top of a closed CO_2 cycle, Frontier Economics (2018) underlines several other sustainability criteria for importing synthetic fuels into Germany: additionality of renewable electricity generation, sustainable use of space, sustainable economic development in the production countries, and in dry climate zones the need to sourcing water from seawater desalination.

The necessity of a closed CO_2 cycle in the long run gives significant interest to the hydrogen enhancement of biofuels proposed by Ilkka Hannula (2016) and his colleagues at the Finnish technical research centre VTT. Renewable-based hydrogen could roughly double the potential of biomass feedstock to produce biofuels, hence alleviating the “fuel vs. food” and “fuel vs biodiversity” concerns. However, while biomass is a precious and relatively scarce resource globally that needs to be mobilised sustainably (IEA 2017d), it still represents an important resource in Northern Europe, which offshore wind power could help utilise in an optimal manner.

Discussion and conclusion

The vast offshore wind power potential of Northern Europe could play a considerable role in helping decarbonise the European economy, beyond its current power sector. It would support the decarbonisation of the transport system, of the energy use in buildings, and help provide enough power to decarbonise industrial sectors of considerable importance, chemicals, steelmaking, and possibly or partially cement making.

Besides all direct uses of electricity, offshore wind power could also run the production of storable and transportable fuels, which could help fill the gaps of electrification in all end-use sectors, i.e. for some industry uses, provide long-term storable fuels for balancing plants, thus increasing the security of supply, and fuels for various long-haul transportation applications.

In most cases, the costs of producing hydrogen as a first building block for manufacturing hydrogen-rich chemicals and fuels, may remain higher than the cost of producing hydrogen from fossil fuels, even if these costs are increased by implementation of carbon capture and storage or re-use. However, a fuller analysis could give a positive value to two important aspects of producing hydrogen from offshore wind in Europe: greater energy security, and lower price volatility.

The decarbonisation of the European industry will likely require massive amounts of additional green electricity and green hydrogen-rich chemicals and fuels. If both electricity and hydrogen were to be produced from NG with CCS, Europe would massively scale-up its NG imports. This could possibly its costs and its dependence on providers.

Furthermore, like a sound financial portfolio associates high-return high-risk shares with low-return low-risk (treasury) bonds, a sound energy mix should associate lower-cost fuels, such as imported fossil fuels, with lower-risk fuels (Awerbuch and Berger, 2003). Using cheap imported NG-based hydrogen with CCS, and very price-stable and domestic renewable-based hydrogen, could represent an optimal portfolio.

Still, manufacturing green materials or fuels easy to store and transport may have to compete with similar products from regions with better, cheaper and larger solar and wind resources. There appears to be nevertheless scope for a considerable expansion of offshore wind power in Northern Europe if European countries are to lead to the way towards a decarbonised global economy.

To sum up, a sound policy for Europe might follow a double track:

- initiate faster deployment of offshore wind power to unleash a higher economic potential, while at the same time accelerating the direct electrification of its industries;
- and initiate conversations with the authorities of countries with excellent solar and wind resources and potential investors in the renewable capacities, conversion plants and other infrastructures from which a trade of hydrogen-rich chemicals and fuels could develop, for the benefits of both exporting and importing countries. Ammonia production in the closest countries with excellent solar and wind resources, such as North African countries, could offer a good starting point.

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