RENEWABLE HYDROGEN IN THE DANISH ENERGY SYSTEM

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CONTENT

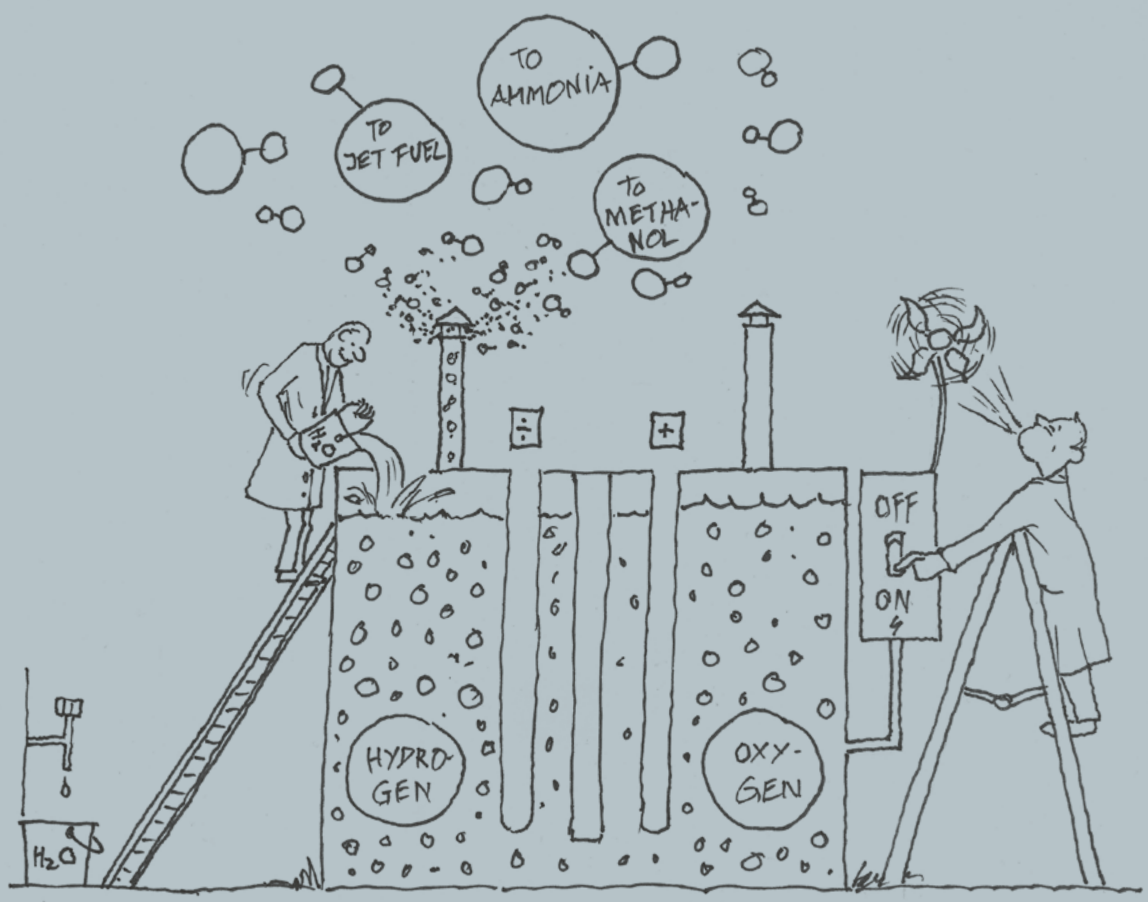
INTRODUCING RENEWABLE HYDROGEN[1] – AND ELECTROFUELS IN THE DANISH ENERGY SYSTEM

Rapid reduction of Danish greenhouse gas emissions is required for fulfilling Denmark's obligation to mitigate global warming. The Danish Parliament aims at reducing greenhouse gas emissions to net-zero by 2050 at the latest. This likely requires net negative CO_2 emissions from the energy sector to compensate for remaining emissions in other sectors such as agriculture and industrial processes. This means that fossil fuels need to be substituted by renewable energy[2] from wind, sun, water and sustainable biomass, the latter being a limited global resource. For this a truly massive scale-up of the installed capacity of primarily wind turbines and solar photovoltaic panels in the electricity sector is required as well as electrification of most of society, including for example transport and heating.

Integrating large amounts of intermittent electricity production based on fluctuating wind and solar radiation into the electric grid is a challenge and requires not only direct electrification of transport and heating (being generally very energy efficient) but also introduction of novel technologies for indirect electrification through hydrogen based derivates (such as ammonia, methanised gas, synthetic fuels) e.g. electrofuels, as well as for the purpose of balancing the electricity grid, for electricity back-up at times with insufficient production to meet demand as well as seasonal energy storage. One crucial mean for this is envisaged to be production of renewable hydrogen. Hydrogen is a storable energy carrier that can be produced from renewable electricity by splitting water into hydrogen and oxygen. This is termed "electrolytic hydrogen" or "renewable hydrogen". Hydrogen production is envisaged to increase the value of wind power by implicitly offering a hedging opportunity for the electricity price. If the electricity price is high the wind turbine will deliver to the electricity-market while the electricity will be stored or converted to a high-value product when the electricity price is low, thus having the positive derived effect of minimizing and level-out periods of electricity prices below LCOE (levelized costs of electricity) of wind.

Hydrogen looks like being an indispensable component in the future energy system in Denmark and globally both as "energy storage" and integration of renewable energy into the entire energy system. Hydrogen can in the future be used directly in heavy-duty road transport vehicles and in the steel industry. It is already today used in fertilizer industry and in oil refining. Hydrogen is also envisaged to be used to produce a variety of different gaseous and liquid fuels (electrofuels) such as for example ammonia, methane, methanol or synthetic jet fuel to substitute fossil fuel (heavy fuel oil, gasoline, jet fuel and diesel) in sectors that are otherwise hard to electrify such as shipping, aviation and heavy-duty road transport industry. Hydrogen and electrofuels can be stored for example in existing oil and gas storages and thereby function as seasonal storage in a future energy system based on fluctuating electricity produced from renewable energy. Likewise, in the future hydrogen could be produced from stand-alone projects featuring for example wind turbines or photovoltaics dedicated exclusively for hydrogen production and could be situated remote from existing electricity grids as

1) European Commission, Renewable Energy Directive 23th April 2009. Article 2: Energy from renewable sources' means energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases.
2) There is also the possibility to produce CO_2-neutral hydrogen from nuclear energy or low-carbon hydrogen from fossil fuels ("blue hydrogen") applying carbon capture and storage (CCS) but this paper focus only on hydrogen from renewable electricity from wind turbines and solar PV and to a more limited extend from sustainable biomass.



HYDROGEN PRODUCTION VIA ELECTROLYSIS

Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer.

hydrogen and various electrofuels can be distributed by pipeline, truck or ship. Denmark has great opportunities for producing hydrogen and electrofuels because of its vast wind resource in the North Sea and coastal areas as well as access to sustainable carbon e.g. from biogas plant.

Electrification is key in the future energy system. According to scenarios from for example the European Commission hydrogen is a necessary building block for EU to fulfil the vision of reducing greenhouse gas emissions to net-zero. This comes to show, among other places, by the European Commission's prioritization of "hydrogen technologies and systems" in its list of 6 Important Projects of Common European Interest (IPCEI)[3]. The purpose of IPCEIs are to boost Europe's competitiveness and global leadership in six strategic and future-oriented industrial sectors and comprise of innovative research projects that often entail significant risks and require joint, well-coordinated efforts and transnational investments by public authorities and industries from several Member States.

The Danish hydrogen industry could play a key role in Europe's future energy solutions on hydrogen. Danish industry is leading-edge on solutions for hydrogen-gas stations and hydrogen fuel cell-based technologies for cars and busses. Also, Denmark's geographical position in terms of ample wind resources and situated next to two major hydrogen-using countries (the Netherlands and Germany) who has proclaimed that they, in the future, depend on hydrogen import could open the possibility for Danish hydrogen export. An export that goes well together with the Danish large unharvested wind resources.

Development and demonstration of hydrogen technologies are therefore no-regret options and need to be promoted at scale.

3) Strengthening Strategic Values Chains for a future-ready EU Industry (5/11-2019)

INTRODUCING RENEWABLE HYDROGEN AND ELECTROFUELS IN DENMARK AND EU

Being the global center of excellence for the wind turbine industry and a growing number of renewable hydrogen technology companies combined with rapid expansion of domestic renewable electricity production Denmark is perfectly suited to grasp the opportunity taking the lead in scaling up renewable hydrogen demonstration projects. Since renewable hydrogen is not yet competitive compared to fossil fuels this requires government planning and public support schemes, a suggested strategy being as follows:

1. Apply government support and incentives to reduce cost of renewable hydrogen and electrofuels
2. Apply government support for demonstrating use of renewable hydrogen and electrofuels in existing and new markets
3. Governments and international organizations should sketch out strategies and implement supporting policies for scaling up renewable hydrogen production – and use in existing and new markets
4. Continue reducing Levelized Costs of Electricity (LCOE) from wind turbines

4) Fertilizers are not currently produced in Denmark

1

- Demonstrate substitution of fossil hydrogen with CO2-free and CO2-neutral renewable hydrogen in existing chemical markets (such as fertilizer and plastic production and use).

- Demonstrate use of electrofuels (ammonia, methanol etc.) based on CO2-free and CO2-neutral renewable hydrogen for ship propulsion.

- Demonstrate use of synthetic jet-fuel based on CO2-free or CO2-neutral renewable hydrogen and sustainable carbon sources such as direct air capture, biogas, gasification etc. for aircraft propulsion.

- Demonstrate use of CO2-free or CO2-neutral renewable hydrogen for road transport.

2

- Large-scale demonstration of renewable hydrogen production from electrolysis and production of electrofuels such as ammonia (for example for shipping), synthetic jet fuel (for example for aviation) and methanol (for example for transport or chemical sector). The task will be to bring down the costs of producing renewable hydrogen and electrofuels. This involves reducing capital expenses (CAPEX) and operational expenses (OPEX) of electrolyzer equipment and wind turbines.

3

- There is a need for the Danish government, the European Commission and international bodies such as the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO) to sketch out short-term (2025-2030) and long-term (2050) Danish, European and global strategies for electrification, energy storage and production of renewable hydrogen and electrofuels to be used in aviation, shipping, road transport and industry.

- These strategies should consider how to scale-up efforts introducing large power-to-x (meaning renewable hydrogen or electrofuels) demonstration projects and promote industrialization in electrolyzer production thus increasing efficiency and bringing cost reductions in renewable hydrogen production.

- Further these strategies should consider how to create a steadily increasing market for renewable hydrogen on short, medium and longer term for example by taxing or capping (in emission trading schemes) CO2-emissions from fossil fuels and by setting requirements for gradually increasing use of renewable hydrogen and electrofuels in existing (fossil) hydrogen markets where hydrogen is used today (fertilizers/refineries) and in new sectors such as shipping, aviation and road transport.

- There is furthermore a need to reform national electricity tariffs and taxing schemes to reduce renewable hydrogen production costs as well as setting up new international standards on how to measure and document whether and to which extent hydrogen is based on CO2-free and CO2-neutral energy sources.

Short-term regulatory recommendations for Denmark:

- Apply CAPEX support for electrolyzer plants, set up Contract-For-Difference support for wind turbines and set targets and requirements for using gradually increasing amounts of electrofuels in aviation, shipping and road transport.

- Create models for regulatory free zones, including 'landingzones' in relation to offshore wind farms, were the use of renewable electricity, renewable hydrogen and excess heat within the zone is not prevented or disincentivized by tariffs and taxes.

4

- Apply support for demonstrating new concepts featuring wind turbines and electrolyzer plants being specifically designed for off-grid applications reducing LCOE from new wind turbine designs.

THE CLIMATE CHANGE CHALLENGE REQUIRES SWIFT ACTION

The central aim of the Paris Agreement is to strengthen the global response to the threat of climate change by keeping global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees.[5] The technological response required is tremendous.

According to the Intergovernmental Panel on Climate Change (IPCC) global CO_2 emissions from fossil fuel combustion and cement production must be reduced by approximately 45 percent by 2030 compared to 2010 and down to zero around 2050 and later in the century there will be a need for net global uptake of CO_2, which will require uptake in forests, plants and soil combined with bioenergy CCS (denamed BECCS, plants capturing carbon released from biomass) as well as direct removal of CO_2 from the atmosphere (direct air-capture)to be permanently stored deep under the surface of the Earth. If technologies for CO_2 capture and permanent storage do not emerge at large scale even larger reductions of CO_2 emissions may be necessary by 2030. The sooner emissions are reduced less need for negative emissions from BECCS at a later point in time being illustrated in the figure below by the difference between the yellow line (early and sharp reductions) and the blue line (later reductions)[6].

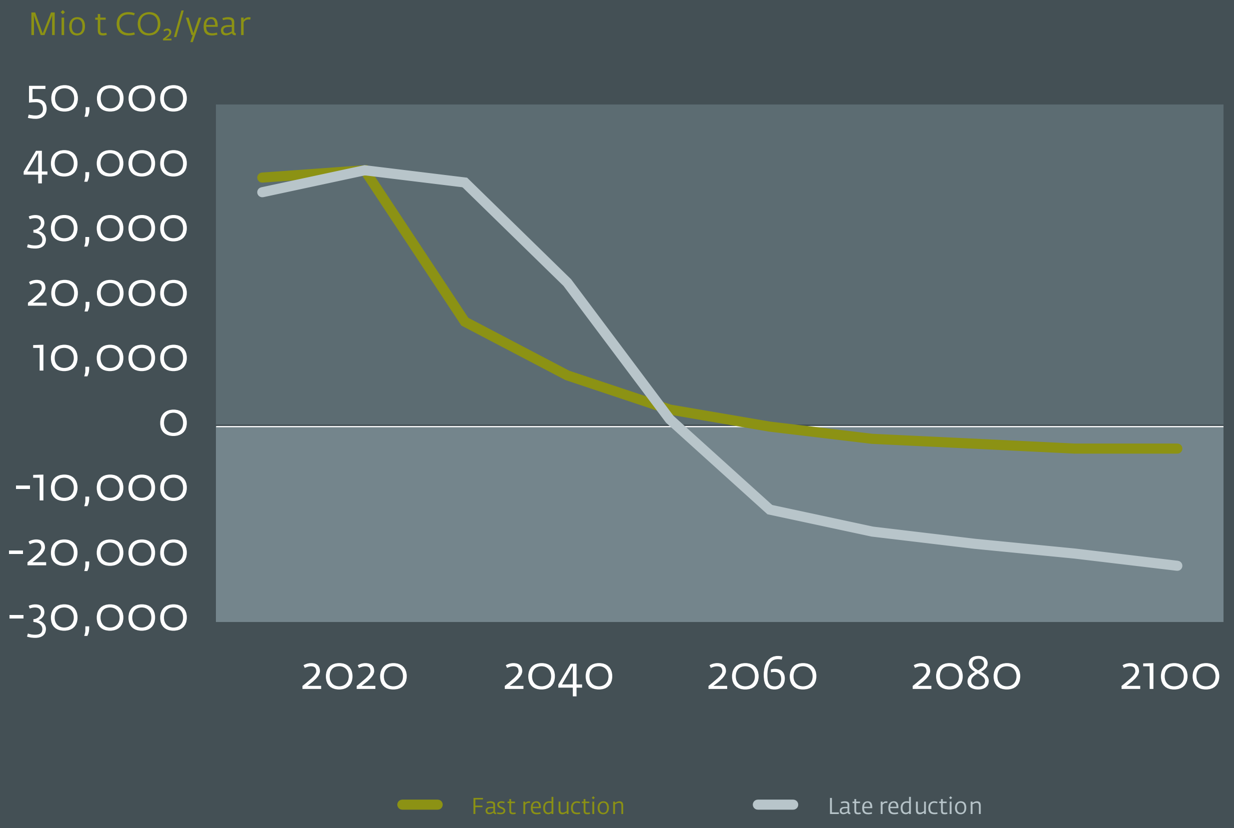
However, with the current policies in place Parties to the Paris agreement are yet no way near reducing global anthropogenic greenhouse gas emissions to the extent required. According to United Nations Environment Program's Emissions Gap Report 2018 global greenhouse gas emissions are growing and not even estimated to peak by 2030, let alone by 2020. The emissions gap assessment shows that the level of ambition in the current nationally determined contributions and policies pledged by Parties to the Paris agreement needs to be roughly tripled for the 2°C scenario and increased around fivefold for the 1.5°C scenario.

Against this background the Danish Parliament agreed in its 2018 energy agreement[9] to pursue the target for Denmark to become greenhouse gas neutral by 2050 at the latest. Meaning that any emissions of all types of greenhouse gases including for example methane and nitrous oxide from agriculture should be compensated by net uptake of CO_2 in forests, agricultural soils or by applying BECCS in the energy sector. A broad majority in the Danish Parliament furthermore aim at reducing Danish anthropogenic greenhouse gas emissions by 70 percent in 2030 as compared to the emission level in 1990. A daunting task requiring political agreement on a range of further not yet defined policies and measures[10].

5) https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
6) https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/
7) https://klimaraadet.dk/da/analyser/status-danmarks-klimamaalsaetninger-og-forpligtelser-2018-0
8) https://www.unenvironment.org/resources/emissions-gap-report-2018
9) https://efkm.dk/media/12222/energiaftale2018.pdf
10) https://kefm.dk/media/12965/aftale-om-klimalov-af-6-december-2019.pdf

Figure 1

Fast reduction of CO_2 emissions eludes need for negative emissions later



Source: Klimarådet, 2018[7]

THE FUTURE IS ELECTRIC

DIRECT ELECTRIFICATION: Many recent scenarios point at electrification as a main ingredient in the future energy system. In light recent technological advancements and cost reductions of wind turbines and solar PV panels as well as batteries some recent scenarios envisage very large potentials for electrifying passenger vehicles, household heating (individual and district heating electrical heat pumps) and various parts of the industry in the coming decades. There is potential for scaling up electricity consumption powered by CO_2-neutral renewables or other low-emission technologies and this is needed to reduce greenhouse gas emissions to net-zero. For example the European Commission envisage electricity's share in total final energy consumption (heat, electricity and fuels used by energy consumers) increasing from one fifth today to three fourths in 2050, and one fourth in the form of e-liquids, e-gas and hydrogen as illustrated in the 1,5 tech-scenario (second from right) in the figure below. This scenario envisages installed capacities of wind turbines in the EU growing rapidly to 450 GW offshore and 750 GW onshore by 2050 as part of a factor 2,5 increase in total gross electricity production.

Due to technological innovation and mass production the costs associated to installing and operating wind turbines and solar photovoltaics producing CO_2-free or CO_2-neutral electricity have in many markets around the world become cheaper than investing in new electricity generating plants using fossil or nuclear fuels on an LCOE-comparison basis and the costs of renewables are expected to drop further in the future[11]. In Europe after a recent major reform the European Emission Trading Scheme (EU-ETS) sets a substantially higher price than previously on emitting CO_2 raising marginal operating costs of incumbent fossil electricity generators thereby increasing electricity price whereby new investments in wind turbines and solar photovoltaics without government subsidies are now gradually being introduced. On this basis and driven by European countries aiming to reduce greenhouse gas emissions renewable energy is set to grow faster in the coming decades and is by many recent scenario studies envisaged to be to a large extent driven by electrification by new sectors such as transport, heating and industrial processes.

INDIRECT ELECTRIFICATION: Many current scenario studies envisioning future low-carbon energy systems based on renewable energies point to electrification of heavy transport, heating and industrial processes as the most important means in combating climate change.

Indirect electrification implies that the heating and transport devices indirectly consume electricity in the form of synthetic fuels / electrofuels. Thus, the indirect electrification firstly always comprises a fuel synthesis, e.g.

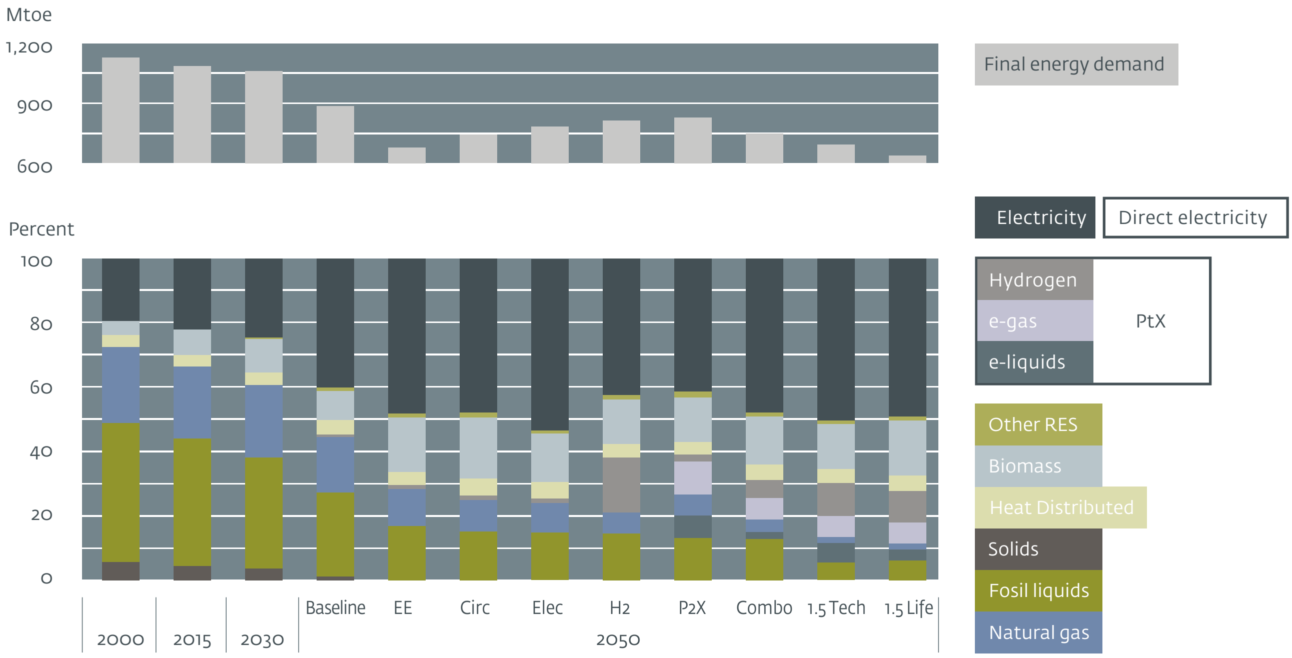
Fischer-Tropsch for jet-fuel and methanation for synthetic methane production.

Scenario studies from for example Eurelectric[12], International Energy Agency[13], European Climate Foundation[14] and the European Commission[15] point

11) https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018
12) https://www.eurelectric.org/decarbonisation-pathways/
13) https://www.iea.org/topics/electricity/futurescenariosforelectricity/
14) https://europeanclimate.org/report-towards-fossil-free-energy-in-2050/
15) https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

Figure 2

European Commision scenarios for shares of different types of energy in EU by 2050



Source: European Commission, 2018[16]

at various ways of achieving large-scale greenhouse gas reductions. A range of different scenarios exist because many various energy technology developments are possible, and the future of the energy system is therefore uncertain because technological advancements and economic developments are interdependent and hard to predict. Figure 3 sketches out how electricity can be used today and in the future. Today electricity is primarily used directly (left side of figure 3) for various processes such as lighting, refrigeration, space heating and cooling, cooking, computing and various processes in households, service, agriculture and horticulture, transport and industry.

Emerging types of electricity use are for example large data centers, individual and district heating (including large heat pumps, geothermal heat plants and heat storage facilities of various kinds), batteries for electric vehicles as well as batteries and other types of technology for grid storage supplementing current pumped hydro storage facilities.

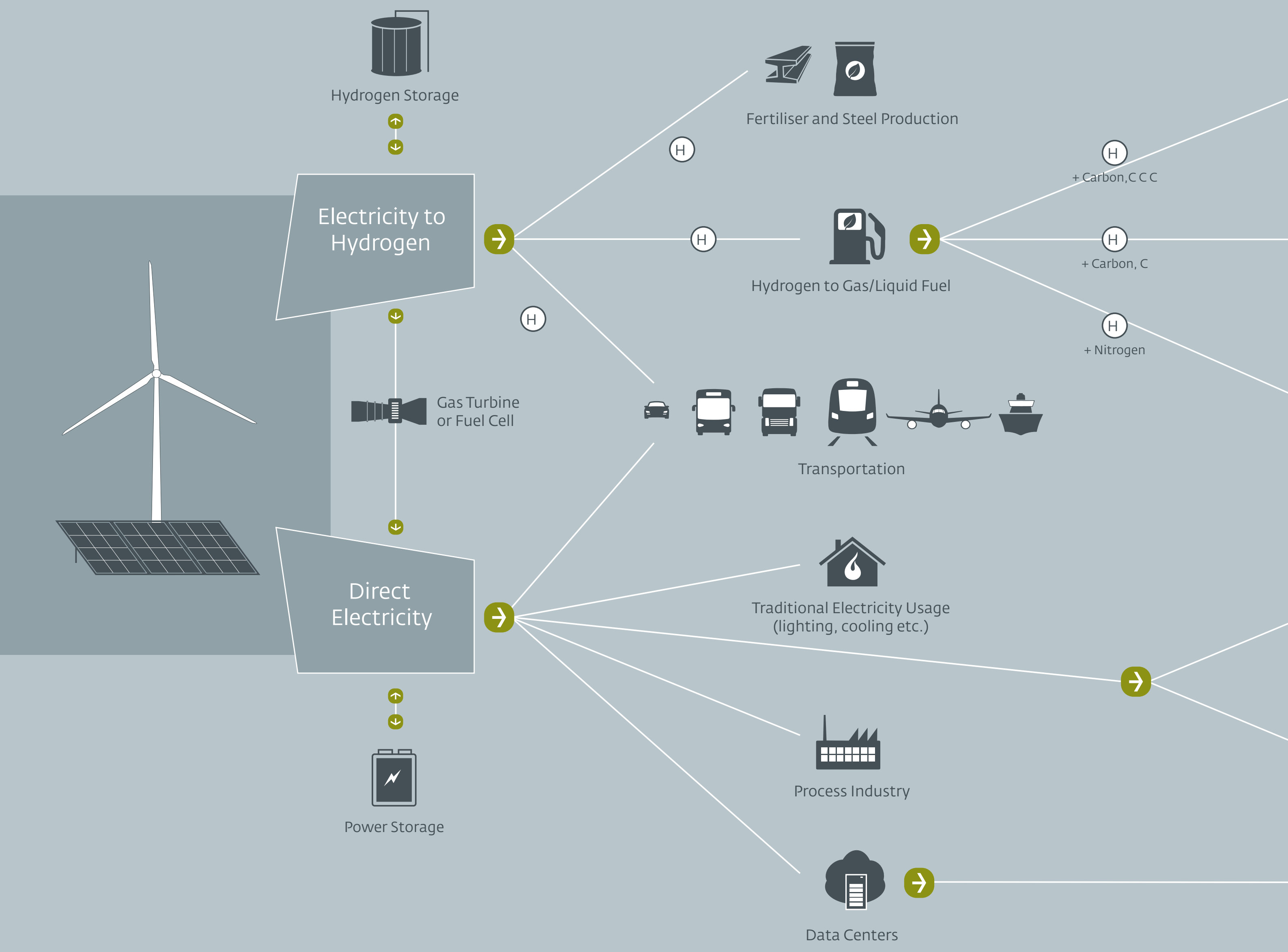
In future (right side of figure 3) electricity is envisaged increasingly being used also more indirectly to substitute fossil oil and gas products that are used for example in heavy-duty long-distance trucks, ships and aircraft that seem difficult to electrify directly because of the high weight and low energy density characteristics of batteries compared to liquid fuels. In current hydrogen production primarily for producing ammonia, fertilizers and for processes in oil refineries and in new industrial sectors such as the steel sector renewable hydrogen is envisaged to substitute fossil oil, natural gas and coal. Hydrogen is also used in demonstration vehicle propulsion projects including both internal combustion engine and fuel cell buses, heavy-duty trucks and other types of road vehicles, although in competition with battery electric vehicles currently being preferred alternative propulsion system by most passenger vehicle producers. For long-haul shipping, aviation and possibly also long-distance heavy-duty road freight alternative fuels based on electricity and to a more limited extend sustainable biomass are needed for the World

16) https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/long-term_analysis_in_depth_analysis_figures_20190722_en.pdf

Figure 3

Electrification

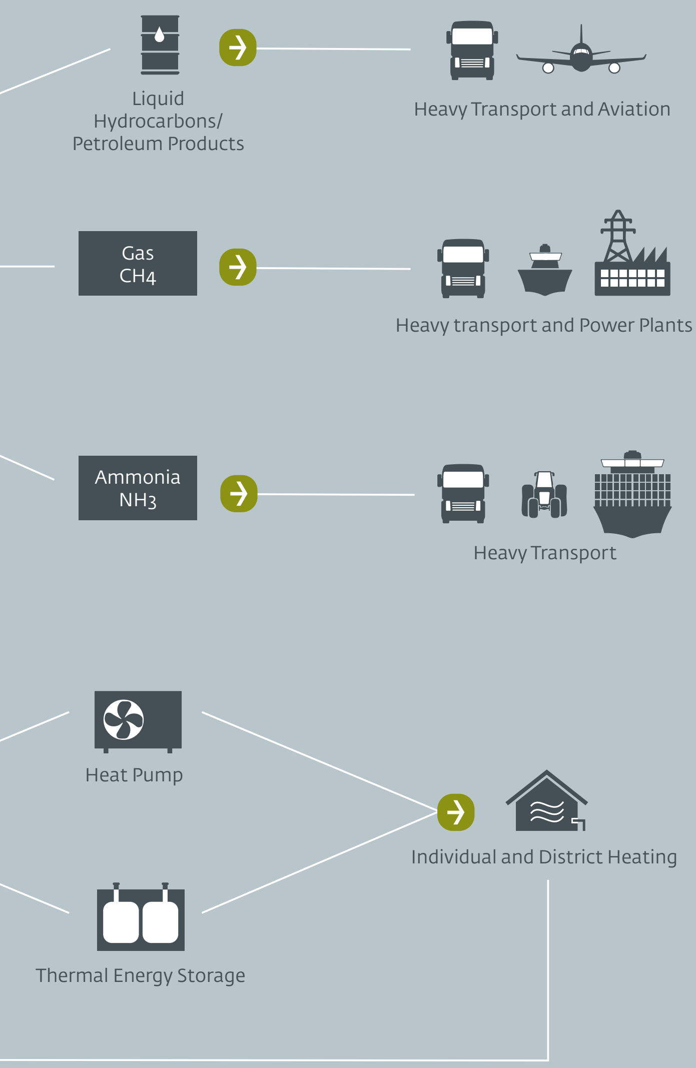
Most of society can be electrified in the future either directly or indirectly via hydrogen as energy carrier.



to quit fossil fuels entirely[17]. Renewable hydrogen and electrofuels are furthermore envisaged for use in gas turbines or fuel cell power plants producing power in circumstances where intermittent renewables cannot meet demand for electricity.

Since sustainable biomass – that is biomass use not causing deforestation or reduced carbon stocks in forests either due to indirect land-use change or overexploitation such as for example residues from agriculture and forests – is a limited global resource, CO_2-free and CO_2-neutral hydrogen and electrofuels are envisaged to be indispensable means in the transition to a fully decarbonized economy (the fifth section of this paper looks deeper into this).

Demonstration and industrialisation: Many technologies needed for increasing electrification of society



Source: Wind Denmark

are available and cost competitive already today or are envisaged to become so within the next decade such as electric heat pumps, electric passenger vehicles, wind turbines and solar photovoltaic panels.

But some of the key technologies[18] that are considered vital for deep greenhouse gas reductions such as fuel cells and renewable hydrogen technologies, various types of electricity grid-storage technologies as well as electrofuels (for example gasification of biomass (pyrolysis) that could also be combined with biochar e.g. storage of the residual char in soils capturing carbon for centuries) are not yet cost competitive and need various degrees of further demonstration and industrialisation scaling up volumes produced to reduce costs per unit. Therefore, as pointed out previously in this report, there is an urgent need to scale up efforts to develop and promote a range of such renewable hydrogen-related technologies.

17) There may also be scope for direct electrification or hybridization in short-haul aviation and shipping by using a combination of fuels and electricity from batteries. For example, aircraft using fuels for take-off and electricity from batteries for the cruise phase and electric long-haul heavy-duty trucks powered by high-power low weight batteries or power lines above major highways if such technologies are developed and commercialized.

18) There is also a need for developing lots of other key technologies that are not in focus in this paper. Some of the most important being technologies for permanent carbon capture and storage (CCS) that may be needed in certain industrial installations such as cement factories and bioenergy with permanent carbon capture and storage (BECCS) offering the possibility to create negative emissions of CO_2 that may be needed to compensate for unavoidable or hard to abate anthropogenic emissions of greenhouse gases from for example agriculture.

RENEWABLE ELECTRICITY, BALANCING AND STORAGE

Integrating large amounts of fluctuating renewable electricity into electricity grids will in the future pose considerable challenges balancing and matching production to demand and vice versa. This is due to the fluctuations in wind and solar insolation. In Danish climate solar photovoltaics – which only produce in daytime at sunlight – typically produce most electricity in summertime whereas wind turbines – which can produce 24 hours a day if there is wind – typically produce most electricity in the winter and generally have much higher yearly capacity factors than solar photovoltaics.

Flywheel Energy Storage (FES) and batteries, makes it possible to store electricity for seconds, hours and days. According to Bloomberg New Energy Finance battery production costs decreased rapidly in recent years and global production capacity is being scaled up to supply increasing amounts of batteries for battery electric vehicles that are envisaged to become cost competitive to internal combustion engines within the next decade[19]. These car batteries can to some extent be usable as flexible storage options for fluctuating power production from wind and sun. Batteries are also emerging in the power sector for grid-storage and -stabilization, increasingly in hybrid combinations with intermittent solar photovoltaics or wind power plants. Today the major part of battery production is based on precious and expensive metals and other materials. In the future, batteries based on cheaper materials might emerge, such as solid-state batteries for electric vehicles or large flow batteries designed specifically for grid-backup[20 21].

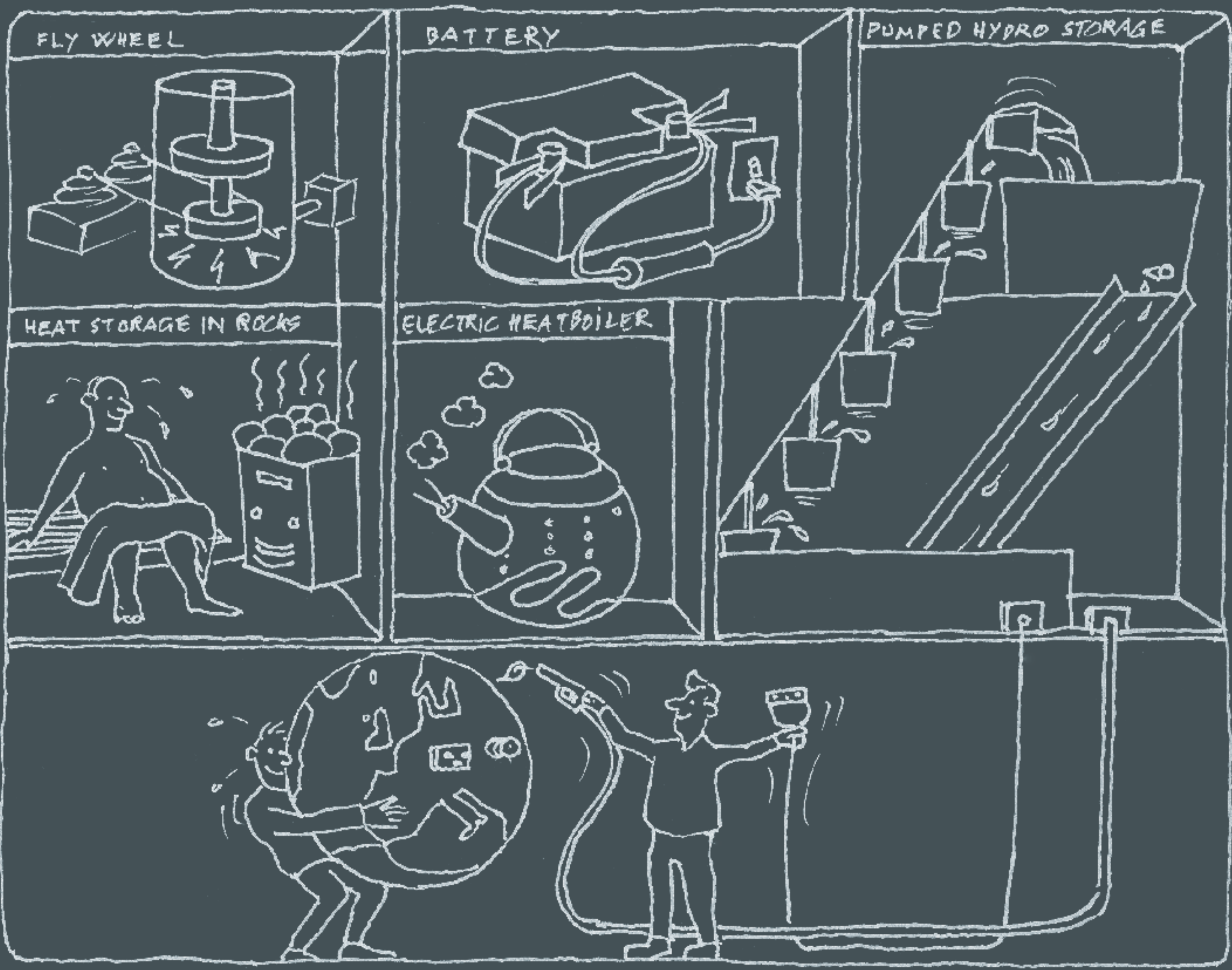
Scenarios for future energy systems based almost entirely on fluctuating renewable energy sources foresee the need of extending and supplementing pumped hydro storage already available in many electricity markets with substantial additional large-scale long-term storage – some of it monthly or even seasonal storage – to be able to supply fuels to the transport sector and to meet demand for electricity throughout longer periods of time where wind turbines and solar photovoltaics cannot meet demand for electricity because of low winds and low solar insolation.

Sector coupling with the heating sector is another option for balancing and storing intermittent electricity. In northern countries like Denmark using electric heat pumps and boilers in low temperature district heating networks is already today a viable option in balancing the electricity grid with the potential of a large upscaling. This potential is realized by substituting current thermal combined heat and power plants with more electric heat pumps and boilers, as well as in the near future dedicated storage facilities for low temperature heat. One further not-yet commercial option is high temperature heat storage in rocks, salt or other media that can power steam turbines delivering electricity back to the grid with the possibility to use the residual low temperature heat in buildings via district heating networks.

Power-to-gas and power-to-fuels (via hydrogen from electrolysis) offer potential for storing very large amounts of energy because the demand for such fuels is several times larger than current electricity production while infrastructure for storage and distribution is already to some extent available. And the gases and fuels can also be used for back-up generation of electricity using for example gas turbines, combustion engines or fuel cells as illustrated in figure 3.

19) https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/
20) https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets
21) https://www.energy.dtu.dk/nyheder/nyhed?id=%7B9D547912-861B-493E-9748-0CD007B0B8A0%7D

Direct and indirect electricity storage



Some studies[22] emphasize the key role that extra marginal electricity consumption for electrolytic hydrogen production plants could potentially play in maintaining the value of electricity from wind turbines and photovoltaics that tend to cannibalize on their own settlement price in spot markets for electricity at high penetration levels because these generators have very low operational costs. To a certain point there can be a key role for renewable hydrogen to be produced from "surplus" electricity at points in time with for example high winds and low demand for electricity meaning low price for electricity in the spot market or even curtailment that is stopping turbines to avoid grid overload. Although as long the investment cost (CAPEX) of electrolyzer equipment is high only producing renewable hydrogen at times where the price for electricity is low increases CAPEX' share as well as the total cost of producing the renewable hydrogen (further explained in next section). The rationale for using hydrogen as media for electricity storage – hydrogen being a so called energy carrier – should be seen in light of costs associated to competing technologies for electricity storage or heat storage as well as the demand and willingness to pay for renewable hydrogen, being (as also described in the next sections) based on CAPEX costs of electrolyzer equipment as well as costs of electricity from wind turbines and solar photovol

22) Energinet, Systemperspektiv 2035, 2018 & PtX i Danmark før 2030 (2019).

INDIRECT ELECTRIFICATION – "POWER-TO-X" – RENEWABLE HYDROGEN AND ELECTROFUELS

In the future a part of electricity consumption is envisioned to become "indirect" (as shown in figure 3). The terms "indirect electrification" or "power-to-x" cover a range of different uses and technologies. First, power-to-X can refer to various electricity conversion, energy storage, and reconversion pathways that utilize electricity. Second, "power-to-X" can refer to conversion technologies that allow for the decoupling of power from the electricity sector for use in other sectors such as heating of buildings, transport and in the chemical industry.

The "X" in the terminology can for example refer to one of the following: Power-to-hydrogen, power-to-ammonia, power-to-liquid fuel, power-to-gas, etc.

In this section we focus on power-to-hydrogen (H2), power-to-ammonia (NH3) and power-to-fuel (diesel and jetfuel). These are options for seasonal storage of electricity and for supplying CO_2-free and CO_2-neutral renewable hydrogen or electrofuels to parts of the transport sector that are hard to electrify directly but should be based on renewable energies in the future – primarily heavy-duty road transport, aviation and shipping.

Renewable hydrogen production costs need to be reduced

According to a recent report on the future of hydrogen from the International Energy Agency hydrogen is today primarily used for producing ammonia e.g. for fertilizers and in fossil fuel refining. This current global yearly demand of around 70 million tons of hydrogen is responsible for annual global CO_2 emissions of around 830 million ton because hydrogen is almost exclusively produced from fossil natural gas (using around 6% of global natural gas consumption) and coal (using around 2% of global coal consumption) being currently many times cheaper than renewable hydrogen.[23]

The CO_2 emissions from hydrogen production can be mitigated if hydrogen is instead produced in natural gas or coal plants equipped with carbon capture and storage (CCS) technology – although this does only partially reduce emissions[24].

CO_2 emissions can be entirely abolished by producing instead renewable hydrogen using electricity from CO_2-free or CO_2-neutral energy. A process currently representing less than 0,1% of global hydrogen production.[25]

Renewable hydrogen production is still a long way from being cost competitive to hydrogen production

23) IEA, The Future of Hydrogen, 2019. According to the report a further yearly 45 million tons hydrogen is separated from natural gas in steel and methanol production.

24) According to the IEA hydrogen production from natural gas can be produced at 1-1,8 USD/kgH2 (cheapest in United States and most expensive in China) and with CCS at 1,2-2,5 USD/kgH2 (cheapest in Russia and most expensive in China), but this will only reduce emissions by approximate half and costs will increase to reach higher reduction levels. For electrolytic hydrogen to compete with these prices will require low-cost electricity from renewables and reduced cost electrolyzers coupled with pricing CO_2 emissions from fossil fuels and either willingness for energy consumers to pay a higher price for CO_2-neutral hydrogen or regulatory measures like requirements for increasing use in certain countries or sectors.

25) According to the report The future of hydrogen (IEA 2019) the cost of electrolysers may be reduced to 450 USD/kWe (200-900 USD/kWe as shown in the table above) in 2050 from today's 900 USD/kWe (500-5600 USD/kWe as shown in the table). The capacity factor (annual operating hours), efficiency and lifespan of electrolyzer unit are also important parameters affecting production cost. And there might be revenue streams from selling oxygen (for instance for oxyfuel combustion in combination with BECCS) and waste heat to third parties (for instance district heating networks).

based on fossil fuels. The two most important factors affecting electrolytic hydrogen production cost are capital cost (CAPEX) of the electrolyzer equipment and electricity price, the latter being the single most significant factor. Improving efficiency and reducing the price of electrolyzers and electricity from renewables are therefore the two most important elements in bringing down the cost of renewable hydrogen production.

There are three main types of electrolyzer equipment: 1) Alkaline, 2) PEM (Protone Exchange membrane) and 3) SOEC (Solid Oxide Electrolyser Cell) featuring different overall efficiencies and at differing development stages as well as envisaged future sizes and a range of other characteristics. The illustrations below from the IEA report on the future of hydrogen illustrate that alkaline are today both more efficient and cheaper than PEM, while SOEC being currently much more expensive holds the promise of becoming both cheaper and more efficient on the longer term. The main reason electrolysers are expensive today is that only around 250 MW in total are installed globally and costs are expected to plummet in future as electrolyser production volumes as well as individual electrolyser plant size is scaled up.

If electricity from renewables becomes available at around or below 30 USD/MWh (0,2 DKK/kWh) at around 4500 full load hours per year and electrolyser equipment cost is reduced to for example 450 USD/KW and electric to hydrogen efficiency increased to around 69% (lower heating value) electrolytic hydrogen production cost may as shown in figure 6 according to IEA be reduced to around 2 USD per kg hydrogen thereby approaching the cost of producing hydrogen from fossil fuels.

How does electrolysis work?

Electrolyzers consist of an anode and a cathode separated by an electrolyte membrane. Different electrolyzers function in slightly different ways, mainly due to the different type of electrolyte material involved.

ALKALINE

Alkaline electrolyzers operate via transport of hydroxide ions (OH-) through the electrolyte from the cathode to the anode with hydrogen being generated on the cathode side. Electrolyzers using a liquid alkaline solution of sodium or potassium hydroxide as the electrolyte have been commercially available for many years. Newer approaches using solid alkaline exchange membranes as the electrolyte are showing promise on the lab scale.

PEM

In a polymer electrolyte membrane (PEM) electrolyzer, the electrolyte is a solid specialty plastic material.

SOEC

Solid oxide electrolyzers, which use a solid ceramic material as the electrolyte that selectively conducts negatively charged oxygen ions (O2-) at elevated temperatures, generate hydrogen in a slightly different way. Solid oxide electrolyzers must operate at temperatures high enough for the solid oxide membranes to function properly (about 700°–800°C, compared to PEM electrolyzers, which operate at 70°–90°C, and commercial alkaline electrolyzers, which operate at 100°–150°C). The solid oxide electrolyzers can effectively use heat available at these elevated temperatures to decrease the amount of electrical energy needed to produce hydrogen from water.

Different characteristics of electrolyser equipment according to IEA

Tabel 1

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long term	Today	2030	Long term
Electrical efficiency (% LHV)	63-70	65-71	70-80	56-60	63-68	67-74-	74-81	77-84	77-90
CAPEX	500	400	200	1,00	650	2000	2,800	800	500
(USD/kW$_e$)	1,400	850	700	1,800	1,500	900	5,600	2,800	1,000

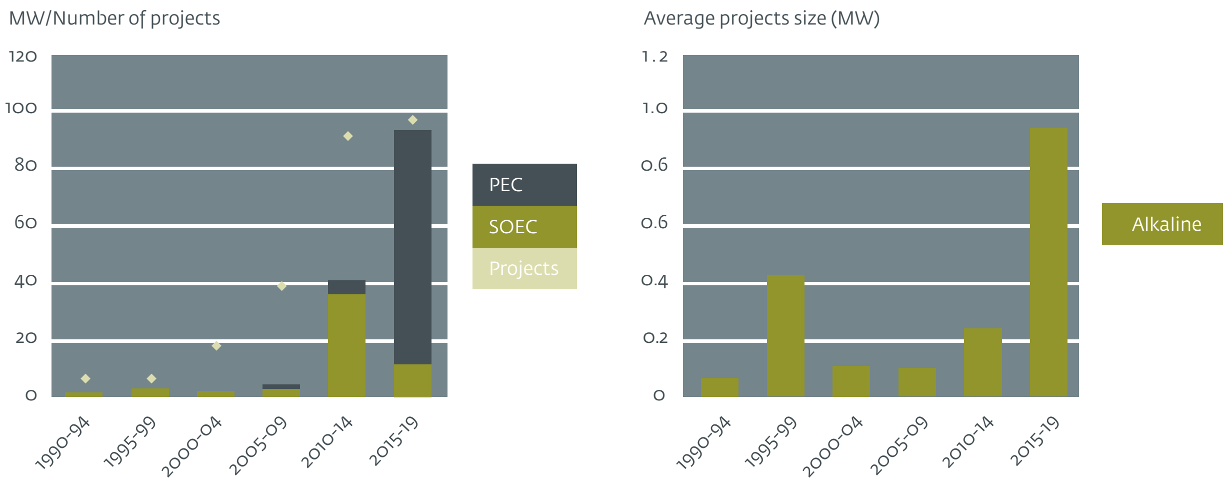
Source: IEA, The future of hydrogen, page 45

Notes: LHV = lower heating value; m²/kW$_e$ = square metre per kilowatt electrical. No projections made for future operating pressure and temper ature or load range characteristics. For SOEC, electrical efficiency does not include the energy for steam generation. CAPEX represents system costs, including power electronics, gas conditioning and balance of plant; CAPEX ranges reflect different system sizes and uncertainties in future estimates.

Sources: Buttler and Spliethoff (2018), "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: a review"; Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), The Future Cost of Electricity-Based Synthetic Fuels; NOW (2018), Studie IndWEDe Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Warme; Schmidt et al. (201 7), "Future cost and performance of water electrolysis: An expert elicitation study"; FCH JU (2014,) , Development of Water Electrolysis in the European Union, Final Report; Element Energy (2018), "Hydrogen supply chain evidence base".

Figure 4

Development of electrolyser capacity additions for energy purposes and their average unit size



Note: Capacity additions refer to already installed capacity additions and are cumulated over the specified 5-year periods.

Sources: IEA analysis based on Chehade et al. (2019), "Review and analysis of demonstration projects on Power-to-X pathways in the world", IEA (2018), World Energy Investment, and the World Energy Council (2018), "Hydrogen an enabler of the Grand Transition" and data provided by IEA Hydrogen Technology Collaboration Programme.
Different characteristics of electrolyser equipment according to IEA.
Source: IEA, The future of hydrogen (2019), page 45.

CONCLUSION

There is a need to scale up and industrialize electrolyzer production. Increasing the size and quantities of electrolyzers produced is envisaged to bring down electrolyzer costs considerably. And for this scale-up initially government support for large-scale demonstration electrolyzer projects is needed.

Use of renewable hydrogen in industry viable, but cost reduction is needed

With declining costs for renewable electricity, in particular from solar photovoltaics and wind turbines, interest is growing in renewable hydrogen and the future theoretical potential use is substantial. Producing all of today's dedicated yearly fossil hydrogen output for fertilizers and refineries of around 70 million tons from electricity would according to the International Energy Agency result in an electricity

Figure 5

Future levelised cost of hydrogen production by operating hour for different electrolyser investment costs (left) and electricity costs (right)

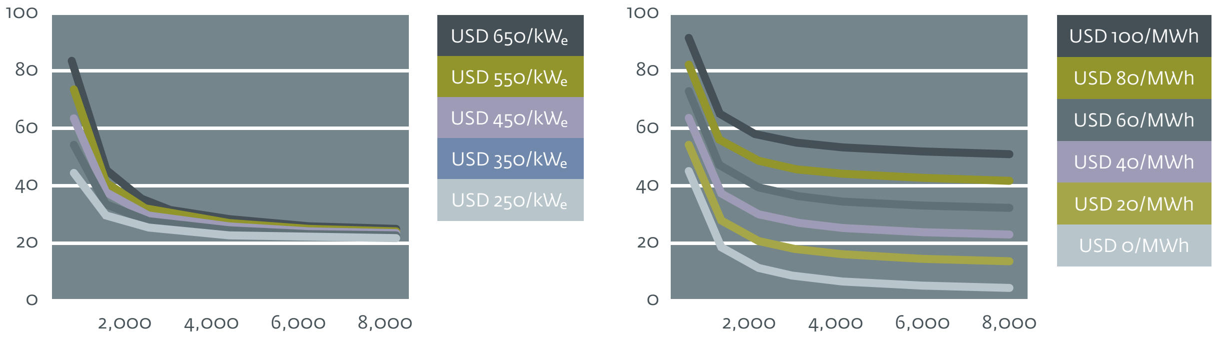


Figure 6: Main components in renewable hydrogen costs according to IEA.
Source: IEA, The future of hydrogen (2019) page 47.

demand of some 3600 terawatt hours (TWh), more than the total annual electricity generation of the European Union. According to the IEA-report *The future of Hydrogen* depending on regional differences in natural gas prices, renewable hydrogen might become able to compete with hydrogen from natural gas with CCS at low electricity prices requiring cost reductions for renewable electricity. Bloomberg New Energy Finance has published a report with a more optimistic view than IEA and envisage alkaline electrolyser cost to fall to around 115 USD/KW already in 2030 and with the possibility of hydrogen production price to plummet as low as 1,5 USD by 2030 in places where solar photovoltaics and wind can supply electricity at around 24 USD/MWh[26] (0,15 DKK/kWh).

Potentials for direct use of renewable hydrogen in road transport

Heavy duty road transport:

As shown in figure 3 it is possible to use hydrogen in transport vehicles. Direct use of renewable hydrogen in fuel cell vehicles holds the promise of emission-free transport with no emissions of CO_2 and NOx since fuel cells only emit water vapour. Downsides are low energy density of hydrogen compared to petrol and diesel, relatively low overall well-to-wheel energy efficiency compared to battery electric vehicles, higher production costs than fossil fuels and electricity and lack of distribution and fuelling infrastructure. Fuel cells being less energy efficient as energy carrier for electric vehicles than batteries are still at earlier development stage than battery electric vehicles and therefore currently mainly used in demonstration projects in for example passenger vehicles and buses, trains, heavy-duty vehicles and marine vessels.

However, the technology could prove to get marked ready with fast phase. Germany shows to build a significant amount of hydrogen refuelling stations (currently one every two weeks). The German governments hydrogen strategy reserving 3,4 billion euro to further construction of hydrogen refuelling station infrastructure. This will be an ad-on to the budget that is already being spent on further hydrogen infrastructure.

A German study shows a number of advantages in development of hydrogen filling stations compared with power stations for electrical vehicles is 1/3. Furthermore, a Mckinsey study conclude that the cost of filling a vehicle with hydrogen is 50% less compared with the equivalent for a battery driven truck.

Additionally, rapid development within hydrogen trucks. Reneau launched in 2019 two hydrogen powered vehicles both for the heavy duty and for lighter

26) https://www.bloomberg.com/news/articles/2019-08-21/cost-of-hydrogen-from-renewables-to-plummet-next-decade-bnef

duty trucks. Vehicles that will use the same infrastructure as hydrogen driven private vehicles. Hyundai and Scania have launched trucks in Switzerland and Norway.

In the bus producing sector there already exist several producers who invest in fuell cell technology. The busses are already on the marked and drive around in several European cities. Additionally, more and more companies in the tourist industry see potential for their tourist busses /coaches.

Private vehicles:
As for passenger vehicles the diversity between electricity driven and hydrogen driven transport could be more pronounced. Many car producers currently seem to upscale production of highly energy efficient battery electric vehicles, because battery prices have seen rapid reductions in recent years. However certain sectors could benefit from hydrogen fuel-cell vehicles as well as hydrogen derivates such as methanol or dimethylether (DME) which to some extent can be directly utilised in combusting engines. An example is the taxi-sector who have announced 80/20 (hydrogen and electricity) hybrid cars in order to serve their driving patterns or strategic cooperation agreement between the Danish company Blue World Technologies and the Chinese EV manufacturer AIWAYS with a view to develop a methanol FC-driven vehicle as well as a hybrid SUV

As mentioned in an earlier section it is currently unresolved whether alternatives like battery-electric trucks or highway overhead power-line powered trucks are more viable options than hydrogen fueled fuel cell trucks. It is also uncertain if and when hydrogen might emerge at large scale for heavy-duty road vehicles since use of hydrogen would require an entirely new infrastructure for distribution and fueling. Direct use of hydrogen at large scale for road transport might face the chicken-and-egg problem of vehicle producers being reluctant to develop light-duty passenger vehicles let alone heavy-duty fuel-cell vehicles for long-distance trucking because of lack of distribution infrastructure.

An alternative option which may reduce the cost and mitigate the risk associated to lack of infrastructure, at least in a short- to midterm horizon, could be the utilization of electrofuels or so-called drop-in fuels as they can be blended and combusted in already existing vehicle engines.[27]

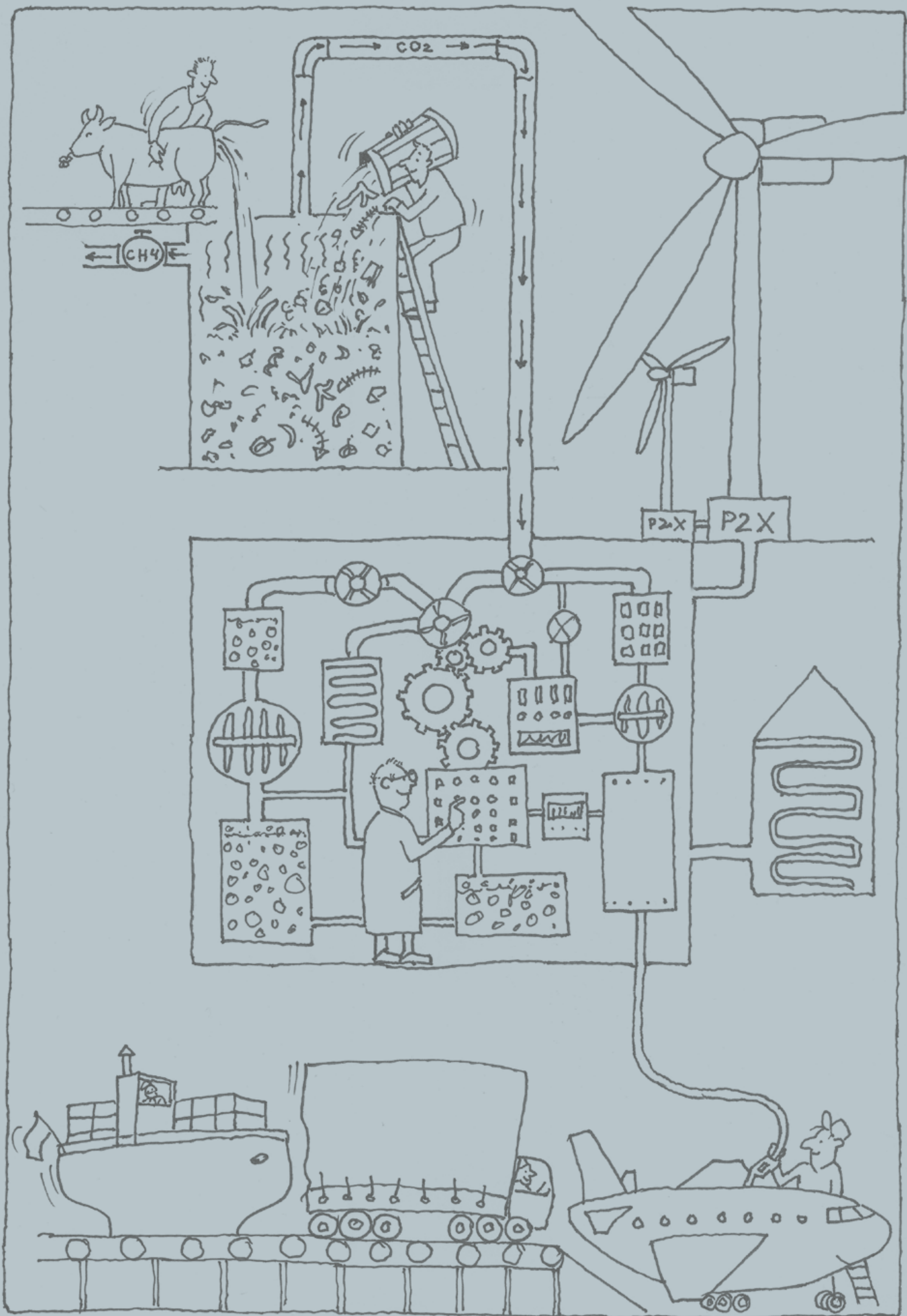
Use of renewable electrofuels in aviation and shipping looks like a no-regret option

For sectors like long-distance heavy-duty shipping and aviation hydrogen or hydrogen-based electrofuels look like indispensable means in the long-term transition to fully decarbonized propulsion systems. To avoid the chicken-and-egg problem of missing hydrogen distribution infrastructure it might be more viable to transform renewable hydrogen into fuels or gases (electrofuels) that are more easily integrated into existing infrastructure and current vehicle and engine designs. In this section we therefore focus on a few types of electrofuels, that is liquid fuels based on renweable hydrogen of which various options exist as illustrated in figure 3.

One option is to produce ammonia for shipping being more energy dense than hydrogen although still considerably less energy dense than diesel and heavy fuel oil requiring larger fuel tanks or more frequent fueling. The merits of ammonia are it can be based entirely on electricity from CO_2-free and CO_2-neutral renewable energy does not require a carbon source. Downsides of ammonia compared to hydrogen and fuel cells are NOx emissions from combustion, issues related to toxicity of ammonia probably being restricted to professional operators and the fact that ammonia-fuelled engines have not been fully developed yet[28]. Production of ammonia is not as energy intensive as many other types of electrofuels (more than 50% efficiency from electricity to ammonia is achievable) and involves capturing nitrogen from the air adding it to hydrogen to produce ammonia (NH3). For example, the Danish company Haldor Topsøe is working on developing high-temperature high-pressure electrolysis P-SOEC capable of producing electrolytic ammonia at a rather high electric efficiency[29].

27) In most instances drop-in fuels can be blended in smaller percentages in existing combustion engines. Higher percentages will require retrofits and/or adding of additives.
28) Man Energy Solution believes it can have the first ammonia engine in operation by 2022
29) https://www.energy.dtu.dk/english/news/2019/04/new-whitebook-on-energy-storage?id=9d547912-861b-493e-9748-0cd007b0b8a0

Main components in renewable hydrogen production



"We have begun a journey towards having net-zero CO_2 emissions from our own operations by 2050. This is an important ambition and one we can only deliver on in collaboration with many other stakeholders"

Søren Skou, CEO of A.P.Møller – Mærsk A/S

Another option is methanol which already today is utilized as a fuel in a few ships and light duty vehicles, thus as of now mainly applied as a key component in the chemical industry[30]. While still considerably less energy dense than diesel and heavy fuel oil, methanol has a higher energy density than both hydrogen and ammonia, requiring smaller fuel tanks less frequent refueling. While almost 100% of methanol production currently is based on natural gas, methanol like ammonia can be based on renewable hydrogen. Though as opposed to ammonia, the downfall of methanol is its reliance on a carbon source, which in the future can be a scarce resource unless the cost of direct air capture is reduced significantly. On the other hand, methanol has very low NOx emissions and is not nearly as toxic as ammonia. Like ammonia, the production process is fairly good with an overall energy efficiency of about 60%.

Both ammonia and methanol can be stored in steel tanks and distributed in pipelines, tanker ships or tanker trucks and can burn in retrofitted and/or specific developed internal combustion engines and thus believed to be a viable option for long-range shipping. The potential is in theory very large since shipping accounts for more than 2 percent of global anthropogenic CO_2 emissions already today – and is expected to consume around 6 million barrels of oil per day by 2030[31]. Emissions from international shipping could grow between 50% and 250% by 2050[32] unless the shipping sector switches from fossil to alternative CO_2-free and CO_2-neutral fuels (to achieve the sector target set by IMO to reduce the total annual CO_2 emissions by at least 50% by 2050 compared to 2008).

As an example, the Danish shipping company Maersk has set a goal to become carbon neutral in 2050 and in a statement points to ammonia and methanol [alcohols[33]] as two out of the three most promising future marine fuels[34]. Besides reducing the production costs of both marine fuels and continue develop and demonstrate applicability of both fuels in the marine sector, carbon pricing or equivalent policies would probably be needed to reduce the cost gap between ammonia/methanol (from renewable hydrogen) and fossil fuels to enable significant offtake of ammonia/methanol from the shipping sector. For example, IRENA in a recent report states as a preliminary finding that renewable electrolytic ammonia may not reach cost parity with fossil fuel before 2050 but anyhow point at ammonia as one of the most promising fuels to decarbonize shipping[35].

CONCLUSION

Demonstrate use of renewable ammonia and methanol for ship propulsion.

30) Eg. for plastic production
31) https://www.iea.org/tcep/transport/shipping
32) http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx
33) Includes ethanol
34) https://www.rivieramm.com/news-content-hub/news-content-hub/maersk-alcohol-biomethane-ammonia-are-best-to-reach-zero-net-emissions-56615
35) https://www.irena.org/publications/2019/Sep/Navigating-the-way-to-a-renewable-future
36) Non-oxidised pyrolysis of biomass into a so-called syngas mixture of carbon and hydrogen

Yet another option is to produce jet fuel based on a mix of renewable hydrogen and hydrogen and carbon from from gasified biomass[36] of sustainable origin or from synthesis of electrolytic hydrogen and carbon captured either directly from the air or from flue gas from for example a biogas plant or a biomass fired combined heat and power plant. One of the merits of such synthetic hydrocarbon fuels being high energy density and usability in current aircraft engines. Downsides are emissions of CO_2 and that carbon from sustainable biomass is likely to become a limited resource in the future. Synthetic jet fuels based on renewable sources are yet far from being cost competitive to fossil jet fuel and their production needs in various degrees further development, demonstration and industrialization scaling up in volumes produced to reduce their costs. Like it is also the case for the shipping sector mentioned above producing jet fuel for the global aircraft fleet would require significant amounts of electricity as well as biomass or other carbon sources such as CO_2 captured directly from ambient air or from combustion flue gases from fossil fuel plants (using the carbon twice before being emitted to the atmosphere, so called CCU – Carbon Capture and Usage). But for electrofuels to be used in aviation substantial reduction of cost of renewable hydrogen as well as carbon pricing or equivalent policies would be needed to reduce the cost gap compared to fossil fuel.

CONCLUSION

Demonstrate use of jet-fuel based on CO_2-free and CO_2-neutral renewable hydrogen.

How to create a market for renewable hydrogen: Focus on possible off-takers

Some studies envisage hydrogen supplying up to one quarter of Europe's final energy demand by 2050. To illustrate the scale this equals 2250 TWh hydrogen which would require approximately 4500 TWh electricity equaling for example a yearly production from around 1000 GW offshore wind turbines. Hydrogen Europe's Hydrogen Roadmap Europe report highlights a range of possible off-takers and dividing those into options, opportunities, short- and medium-term no-regret and long-term no regret (illustrated in the figure below).

First step towards realizing such a hydrogen scenario would be addressing possible off-taking sectors finding out their willingness to pay for substituting fossil fuels with renewable hydrogen or electrofuels relying probably ultimately on consumer preferences, prices and political targets.

Most likely many sectors of society will end up using electricity directly. But for some sectors like aviation, shipping and high temperature industrial processes renewable hydrogen and electrofuels seem like no-regret long-term moves.

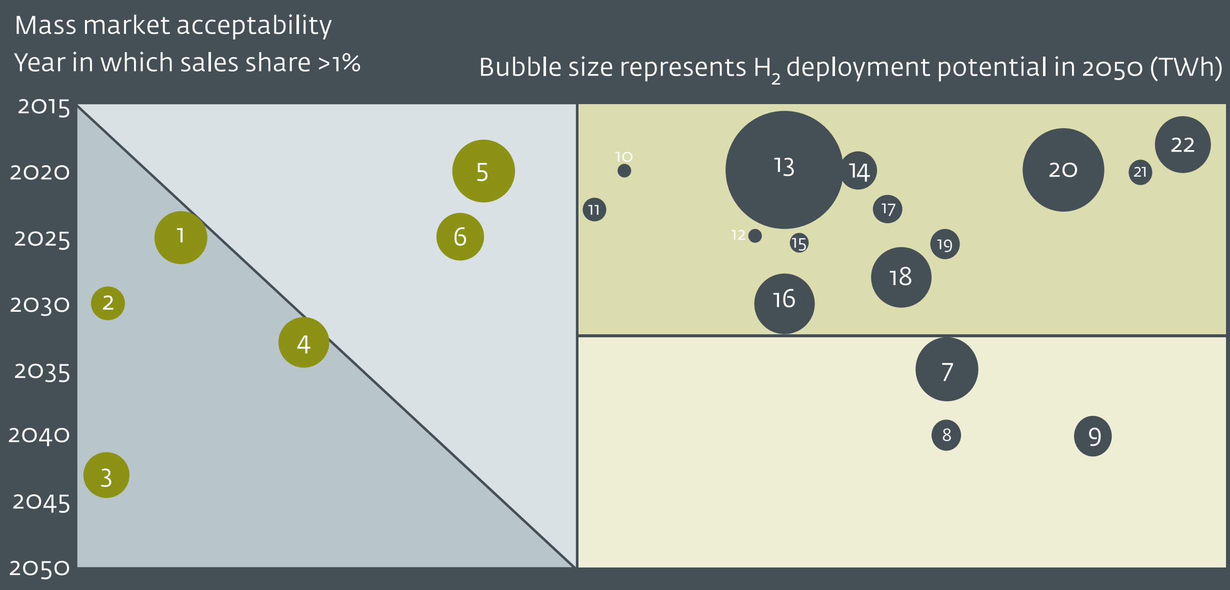
Substantial cost reduction and political targets needed for electrofuels to become viable options at larger scale

According to a recent review study[37] of estimates of the potential production costs of various types (methane, methanol, dimethyl ether, diesel, and gasoline) of carbon-based electrofuels produced from carbon dioxide (CO_2) from for example biomass and water (H2O) using electricity (renewable hydrogen production) as the primary source of energy it is very hard to estimate current and future prices. Cost estimates in the literature including production, distribution and dispensing ranges from 75-26.000 DKK/MWh of fuel and the authors of the review study predicts plausible costs in the range of 400–600 2015DKK/GJ of fuel in 2015 and 300-450 2015DKK/GJ of fuel in 2030. This corresponds to fossil fuel prices (as of 2018) of gasoline and diesel of around 110 DKK/GJ and biodiesel and bioethanol prices of around 230 DKK/GJ . From this study it thus seems unlikely that hydrocarbon electrofuels will be able to compete economically with fossil oil price before 2030, unless a carbon tax is applied to emissions of CO_2 and the tax level needed would likely have to be substantial and in the order of 3.000-6.000 DKK/tCO_2 (Wind Denmark estimate). As this is a much higher carbon price than what is seen in carbon taxing and emissions trading schemes it may therefore prove difficult to promote electrofuels by setting a price on CO_2 only. Perhaps a more plausible way to create a market for electrofuels could be to set binding targets for oil companies[38] to blend gradually increasing amounts of electrofuels in diesel and jetfuel used for long-distance shipping vessels, heavy-duty long-distance road transport and aircraft or to set greenhouse gas reduction targets for the shipping, aviation and heavy-duty road transport sectors in a way that enforce operators to use increasing amounts of for example ammonia or other electrofuels.

37) https://www.sciencedirect.com/science/article/pii/S1364032117309358.
38) The same way biofuels are promoted in EU today.

Figure 6

Hydrogen can according to Hydrogen Roadmap Europe in principle be used in many parts of society



Options

1. CCU (methanol, olefins, BTX)
2. Small cars
3. Low-/medium-grade heat
4. Power generation

Big opportunities

5. Mid-sized cars
6. Vans/minibuses

long-term no-regret moves

7. High-grade heat
8. Synfuel in aviation
9. Synfuel for freight ships

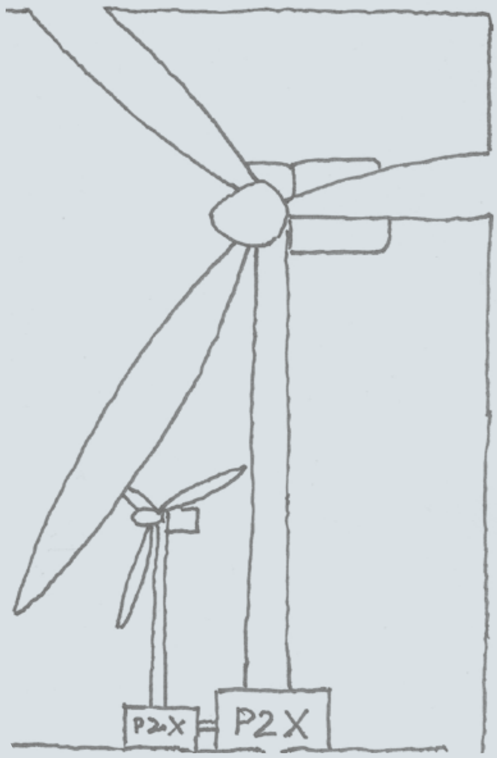
Short- and medium term no-regret moves

10. City buses
11. Large cars
12. Passenger ships
13. Building heating
14. Taxis
15. Coaches
16. Trucks
17. Forklifts
18. Steel (DR)
19. Trains/tramways
20. Amonia/Methanol
21. Renewables integration[1]
22. Refining

Source: Hydrogen Roadmap Europe:https://www.hydrogeneurope.eu/news/hydrogen-roadmap-europe-has-been-published

REDUCING LEVELIZED COSTS OF ELECTRICITY (LCOE) FROM WIND TURBINES

The LCOE of wind turbines has been reduced substantially in recent decades and in many markets around the world both land and sea-based wind turbines are now cheaper than new thermal power plants based on either fossil fuels or nuclear energy. According to for example IRENA further LCOE reductions are expected in future due to further technological development[40]. Further to this it is possible to develop cheaper wind turbines specifically designed for off-grid applications. According to the International Energy Agency in the future there is scope for initiating very large off-grid hydrogen production facilities in remote geographical locations[41]. For example, early sketches for hydrogen production plants in the gigawatt range in Australia have been unveiled[42]. For stand-alone off-grid plants either on or offshore new types of wind turbine designs can be envisaged to reduce LCOE of wind power further.



This leads to:

CONCLUSION

Apply support for demonstrating new concepts featuring wind turbines and electrolyzer plants being specifically designed for off-grid applications reducing LCOE from new wind turbine designs.

40) https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf.
41) https://www.iea.org/reports/the-future-of-hydrogen.
42) https://www.pv-magazine.com/2019/10/08/siemens-backs-5-gw-green-hydrogen-plan-for-australia/.

FUTURE REGULATORY CHALLENGES

Some changes to the regulatory framework are needed to support development of a renewable hydrogen economy:

Tariffs on electricity: Cost of producing electrolytic hydrogen in grid-connected electrolyser plants will be reduced if electricity transmission tariffs are removed or reduced. In a Danish context Energinet is currently investigating whether to introduce a lower Danish transmission tariff provided electrolyzers connected directly to the transmission grid are willing to accept interruptible power supply at points in time when the transmission load is high. This could be an attractive option for electrolyzer plants that anyway are dependent on low electricity prices that generally occur at lower loads. Further to this it is possible to establish behind-the-meter projects where electrolyzers are powered by electricity from wind turbines and photovoltaics not connected to the electric grid.

CO_2 and energy tax: To support the demand for alternative fuels and avoid border trade, the current CO_2 and energy taxes on transport fuels needs to apply for all alternative fuels and be reduced to a level, or exempted, that makes it more attractive to both purchase more expensive vehicles and alternative fuel.

Refuelling Infrastructure: Availability for refueling of alternative fuels is a prerequisite for the transition of the land-marine- and air-based transportation. It is therefore important that barriers, if any, for establishing the necessary underlying infrastructure as well as the actual refueling station are removed. Given the future transport fuels most likely won't be a one fits all but rather a wide array of different fuels, a long-term infrastructure investment plan incl. funds for deployment, should be developed and continuously revised based on the market trends.

Pricing CO_2 by tax or cap (in an emission trading scheme) can set a price on CO_2 and thereby increase the cost of producing hydrogen from fossil fuels in Europe (but not hydrogen imported from outside Europe): Hydrogen produced from fossil fuels involves CO_2 emissions. These CO_2 emissions are most often not taxed. In Europe emissions from fossil hydrogen production may be subject to emission trading in the EU ETS but can receive free CO_2-allowances thereby not paying for most of its CO_2 emissions. Free CO_2-allowances for renewable hydrogen production within the EU ETS when substituting hydrogen production based on natural gas are requested by some stakeholders (for example Ørsted)[44].

Requirements for EU Member states to use certain percentages of renewable energy in the transport sector: Such provisions are already implemented under the European Directive on renewable energy and from 2021 includes the use of electrofuels – since grid electricity is a mix from renewables, nuclear and fossil sources that receive tradeable guarantees of their origin. For example, renewable hydrogen produced using electricity from power purchase agreements based on guarantees of origin referring to newly installed wind turbines and solar photovoltaics could dampen criticism that additional demand for grid electricity prolongs and increases power production from existing fossil fuel power plants. The terminologies brown (lignite), black (hard coal), grey (natural gas), blue (fossil fuels with CCS) and green (renewable energy) hydrogen refer to different sources of hydrogen production. And hydrogen can furthermore be produced from other sources such as biomass and nuclear. And electrofuels can be based on either only electrolytic renewable hydrogen or mixed with hydrogen from biomass. Therefore, there is a need for these complicated terminologies to be better defined so that the associated CO_2-emissions become clear.

Requirements for aircraft operators and maritime operators to use increasing amounts certain percentages of renewable energy could perhaps be agreed politically in ICAO and IMO. This also requires developing a framework for fair accounting of what can be termed "green" or "renewable" fuels.

44) According to Ørsted this is the case in the Netherlands.

DANISH ACTIVITIES ON HYDROGEN

The Danish Parliament's board on Energy, supply and climate asked the 20th of August 2019 the Danish minister for Climate Energy -and Supply to be informed of the current Power-to-X activities launched in Denmark: The minister was provided with the information in the table/list below.

List of Danish power-to-x projects

Name	Maturity	Input	End product / Energy carrier	Consortium	Info
Greenlab Skive	Full scale	Biogas	methane gas of "naturgas" quality	Green Lab Skive	www.greenlab.dk
SkyClean	Development	Biomass (straw/slurry)	synthesised aviation fuel and bio-char	Stiesdal A/S and partners	www.stiesdal.com
eFuel	Demonstration of pilot-plant	Biogas	methane gas of "naturgas" quality	NGF Nature Energy Biogas and partners	
Fasstofoxid Cell based production and use of ammonia	Development followed by demon-stration	Nitrogen	Ammonia, electricity	Haldor Topsøe and partners (incl. Energinet, Vestas and Ørsted)	
eSMR-MeOH: Biogas to MeOH via electricity	Demonstration of pilot-plant	Biogas	Methanol	Haldor Topsøe and partners (incl. Energinet)	www.energiforskning.dk
Power2Met	pilot test	Biogas	Methanol for trans-port	GreenHydrogen and partners	www.energiforskning.dk
Energilagring – hydro-gen injection in the gas grid	development	-	Hydrogen injected directly into the gasgrid	Energinet and partners	NA
Biocat Roslev	pre-study	Biogas	methane gas of "naturgas" quality	BioCat Roslev aps and partners	www.energiforskning.dk
Wind2H	NA	-	Hydrogen	DTU	www.energiforskning.dk
HyBalance	Demonstration	-	Hydrogen as storage and for transport	Air Liquide and partners	hybalance.eu
Synfuel	Proof of concept	Biogas	Methanol	DTU and partners	www.energiforskning.dk
Technology maturation of ceramic electrolysis. Mature SOEC	pilot test	-	Hydrogen	Haldor Topsoe and partners	www.energiforskning.dk
XEL2GAS	Laboratorial	Biogas	Acetic acid	AAU	www.energiforskning.dk
MegaStoRE	Demonstration of pilot-plant	Biogas	Methane gas of "naturgas" quality	DTU	www.energiforskning.dk
Biocat	Demonstration	Biogas	Methane gas of "naturgas" quality	Electrochaea and partners	www.energiforskning.dk
Electricity improved biogas	Development	Biogas	Methane gas of "naturgas" quality	Haldor Topsoe and partners	www.energiforskning.dk
SYMBIO	Development	Biogas	Methane gas of "naturgas" quality	DTU and partners	www.energiforskning.dk
MegaBalance	analysis	-	-	NEL Hydrogen and partners	www.energiforskning.dk

All projects use electricity and water as input, thus they are not described in the column for "input". For a few of the projects the electricity comes from sustainable energy sources. Other projects are connected to the electricity grid hence gets the electricity from there.

Source: Danish Energy Agency

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