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DANISH ROADMAP FOR LARGE-SCALE IMPLEMENTATION OF ELECTROLYSERS

AALBORG UNIVERSITY
DENMARK

Danish roadmap for large-scale implementation of electrolysers

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Abstract

Water electrolysis is an established chemical process that has been used in industry for many years. The interest of using electrolysis for other purposes than industry is present, but execution of its implementation in the system is behind. This has to change, as the need for electricity storage is increasing with higher shares of intermittent renewable energy in the system.

Storing electrons into chemical energy via electrolysis opens door to cheaper ways of energy storage than direct electricity storage or heat storage. In order to meet the targets for 100% renewable energy in 2050, and to follow the energy system planning projections conducted that include electrolysis as an important part of the future energy system, Denmark needs to start implementing electrolyser capacities in the energy system.

The roadmap divided into 4 phases based on stakeholders' inputs, previous studies on technologies and literature review, gives a set of different activities and measures that needs to be taken to speed up the implementation of electrolysis. Profiling Denmark as an important actor in the electrolysis and electrofuel production is a logical step as country can serve as a test centre for renewable energy integration and balancing technologies due to already high share of renewables.

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Contents

Nomenclature

Abbreviation	Meaning
AEM	Anion exchange membrane
DME	Dimethyl ether
DSO	Distribution system operator
FT	Fischer-Tropsch
PEM	Polymer exchange membrane
P2G	Power-to-gas
P2L	Power-to-liquid
SOEC	Solid oxide electrolysis cell
TRL	Technology readiness level
TSO	Transmission system operator

Summary

Water electrolysis is a well-established electrochemical process and has been available for over 200 years [1], and while its use for industrial purposes has been recognized and actively used from the beginning of the 20th century, deployment of this technology for energy applications never substantially emerged. Globally only 4 % of hydrogen is produced by electrolysis [2], and most of the hydrogen comes from reforming natural gas. Many energy system projections and scenarios, both Danish and international, recognized electrolysis as an important technology for our energy system transition to a more sustainable and carbon neutral future [3–5]. In the political environment, which incentivises converting energy systems to ones with more renewable energy, the need for connecting the fluctuating electricity to all sectors and storage options is crucial.

While today's energy systems are highly dependent on fossil fuels, these fuels are a main source of flexibility in the system. Since the renewable energy systems based on the high share of fluctuating electricity have no flexibility on the resource side apart from biomass, the creation of flexibility in the conversion processes is necessary to create a well-functioning robust system. Electrolysis offers not only the possibility to convert electrons from wind and solar to storable chemical energy but at the same time, it offers an option for system balancing and a source of flexibility. Therefore, it is seen that electrolysis could be the enabling technology for sustainable energy scenarios with restricted biomass resources.

Electricity storage in the form of liquid or gaseous fuels, in which electrolysis is a central part, could also be one of the ways to provide a much needed alternative to transport fuels. Currently, available alternatives for the transport sector, apart from direct use of electricity or battery electric vehicles, are very biomass intensive. With electrification not being suitable for all modes of transport, there is still a large part of the transport demand such as heavy-duty transport, long haul road transport, marine and aviation that needs to be met with renewable fuels in gaseous or liquid form. If only biomass based fuels are to be used that vast areas of land around Europe and the world will have to be utilised to produce transportation fuels. Leaving minimal land for other sectors, nor for that matter being able to meet the full transport demand.

The biomass resources are limited and the biomass potential is subject to a high level of uncertainty ranging from 0 to 1500 EJ [6]. If we add to this criteria the sustainable use and production of biomass, which is crucial in order to limit the environmental impact and not cause an adverse effects on biodiversity, the need for other fuel options is inevitable. In Denmark, the reported biomass potential varies from source to source [3] but it is evident that the potential does not match the demands existing in the energy system for fossil fuels – neither in Denmark or globally. It is therefore important to consider alternatives, other than the available biomass that is also needed for process industry and other parts of the energy system that can overcome the problem of higher demand for hydrocarbons in the energy system.

The need for using electrolysis for energy applications is slowly emerging and some technologies have made significant progress in the last few years in countries around Europe. Power-to-gas (P2G) and biogas upgrade projects in which electrolysers are being tested both for integration of renewable energy but also for production of valuable fuels are being demonstrated around the world.

In 2013, Gahleitner [7] reports that globally there are:

- 41 realized MW size power-to-gas plants
- 7 planned MW size P2G projects

Germany is the front runner in demonstrating the technology on a large-scale usable in renewable energy systems. Regarding power-to-liquid (P2L), there are fewer projects and most of them have only been realized in the last few years [8–10]. There are two realized power-to-liquid plants and two planned P2L projects:

- George Olah plant in Iceland, which produces methanol from CO_2 and hydrogen from alkaline electrolysis
- Pilot plant in Dresden, Germany which produces diesel from CO_2 and H_2 from solid oxide electrolysers
- Luleå, Sweden steel manufacturing plant which will convert CO_2 into liquid fuel
- Duisburg / Lünen, Germany where carbon dioxide from a coal power plant and hydrogen will be converted to methanol

Figure 1 shows the range of fuels that can be produced with P2G and P2L technologies, providing a connection between electricity and fuel storage.

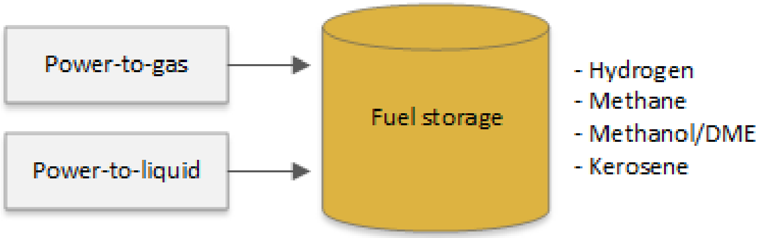

Figure 1. Storing electricity via electrolysis intro different fuel types

There are other potential functions for electrolysis already present on the market. The ones that are more probable to emerge in the short-term, are hydrogen for industrial purposes, niche gas markets, ancillary services and hydrogen as end transport fuel. Industrial use of electrolytic hydrogen is not new and it has been used for fertiliser in countries that have cheap electricity sources. The use of electrolysis in niche markets is already recognized and has started to emerge, however it is not expected that the capacity scale of this market will grow much in comparison to other electrolysis markets. Hydrogen for providing ancillary services is an attractive solution in the current energy system with an increasing share of renewables. Hydrogen as an end fuel option used in fuel cell vehicles for transport is in direct competition to electric vehicles, as opposed to competition with hydrocarbons for long-distance, heavy-duty transport. Direct use of hydrogen is thus not seen as a long-term solution but can be seen as a way to initiate the market creation for electrolysis. The hydrogen fuel cell vehicles will be utilised instead of electric vehicles where there is a need for longer

The future of electrolysis seems most promising in the transport sector for power-to-methane and power-to-liquid fuel production that enables needed cross-sector integration, creation of flexibility and seasonal storage (www.smartenergysystems.eu).

range and fast refuelling, rather than maximizing the fast charger capacity, as this can cause instability in the system.

Denmark is an attractive location for a real-life demonstration of electrolysis, P2G, and P2L due to already high share of renewable electricity in the system, with wind providing around 45% of electricity consumption. With an access to high share of abundant wind at low price and the expectation that the level of wind will be higher than 50% is 2020, by testing in Denmark it will be possible to foresee problems that may occur in other countries when the share of renewable electricity is higher.

Why Denmark is an ideal test-bed and laboratory for large-scale electrolysis:

- **Use and storage of wind power (soon >50% penetration in the electricity grid)**
- **Can test use of intermittent resources and help predict potential problems regarding integration of renewable energy and electricity grids.**
- **Can be connected to district heating to utilise waste heat from fuel production processes**
- **Plan for 100% renewable energy in 2050 (including transport) which requires actions on especially heavy-duty transport.**
- **Research in alkaline, polymer exchange membrane and solid oxide electrolysis cells**
- **Producers of chemical synthesis and**

Electrolysis can be seen as a technology that can help system stabilisation and integration of intermittent renewables, therefore it can operate by following and utilising the excess electricity production and manage the peak production that cannot be exported. This is particularly interesting when additional international cable connections are not able to solve the issue where similar weather conditions in neighbouring countries occur simultaneously. Thus, there is limited opportunity to export the excess wind electricity production to neighbours that are dealing with the same issue. With the agenda to reach 100% renewable energy in 2050, Denmark needs to connect intermittent electricity to all energy sectors and end-uses in order to create flexibility that is lost on the resource side. Systems based on renewable-only energy sources need to utilise new sources of flexibility and electrolysis offers an opportunity to achieve this.

As a part of this roadmap, a number of stakeholders have been interviewed. The interviewed stakeholders agree that electrolysis will play a key role in the energy system when it has a high share of renewable energy, and furthermore it has a different potential capacity utilisation compared to other integration technologies. The biggest potential is seen for the fuel production for transport sector mainly methanol, DME, methane and jet fuel, but in the current market environment where there is not necessarily a need for this technology it will probably emerge in the specialized gas market with hydrogen as the end fuel. Stakeholders do not believe that the use of electrolysis for ancillary services will be the main purpose or the market focus. Rather they believe the additional benefit and revenue stream of using electrolysis will be for transport fuel production in the future.

One of the main obstacles from the stakeholders point of view for the market uptake of electrolysis is the electricity price and the lack of special tariff for the storage of electricity via electrolysis. Furthermore, there is also a need for more demonstrations of commercialized technologies in the desired applications and configurations. While solid oxide electrolysis needs both research and demonstration to reach the commercial stage. Denmark also needs to attract more private investors that can accelerate the implementation of electrolysis, however this requires the creation of a market.

This roadmap for the implementation of electrolysis was created based on the stakeholders input, previous studies, technology status and literature review. The roadmap is divided into four phases: *Market preparation*, *Market uptake*, *Market implementation* and *Large-scale implementation in the smart energy system*. The roadmap looks into different activities, measures and incentives that should be implemented in order to speed up and maximize the implementation of electrolysis. These include demonstration, regulatory measures, technology improvements and needed research.

Roadmap for implementation of electrolysis in Danish energy system

A high share of renewable energy sources within the energy system will generate a need for creating flexibility and energy conversion and storage will be a focal point of the future energy system. The current energy system relies on fossil fuels to provide this flexibility on the resource side, which will be lost in the future, and new balancing options for both conversion and storage technologies will be needed to compensate for the lack of flexibility. Energy storage technologies have different costs, where storing high-density fuels is the cheapest and the least space demanding option [11]. Electrolysis as a part of the power-to-gas and power-to-liquid technology is an enabler for storing electric power as hydrogen. Which can afterwards be utilised either for upgrading biomass and biogas or for bonding with direct CO_2 sources to form methane and different electrofuels. The converted electrons from wind and solar power to storable chemical energy can be utilised in existing infrastructure and can be combined with existing technologies. In 2015, wind power generation represented 42% of the electricity consumption in Denmark [12] and the share will continue to rise. The goal for 2030 is that 50% of the energy supply is provided by renewable energy. Therefore, we need to create a smart energy system [13] that can maximize the use of intermittent electricity by transferring the generated electricity into the demand sectors, heat, mobility and industry. There already exists many technologies for the integration of renewable energy and storage options [11,14], but we are still missing alternatives for heavy-duty transport that do not jeopardize biomass resources. This is where electrolysis has the highest potential. Since the transport sector is complex, the changes required in the infrastructure are capital intensive, and if wrong decisions are made today, they may lead to lock-in issues in the future. Thus, it is preferred that the utility of existing infrastructure, with some alterations, is maximised.

Electrolysis is already widely tested around the world and the necessary demonstration and development activities need to happen for specific applications within combined systems rather than focusing on single technologies. Alkaline and polymer exchange membrane (PEM) electrolysers are commercialized technologies, but solid oxide electrolysis cells (SOECs) are still on the research and development level. Every technology has its advantages and disadvantages, for example alkaline has been present on the market the longest, but it has low efficiencies. However, it is attractive since it uses non-precious metals as catalysts in comparison to PEM. PEM electrolysers are therefore more expensive which hinders their implementation due to cost. SOECs are using cheaper materials since they use ceramic electrolyte therefore being more attractive from the price side. Moreover, they can operate in the reversible mode, both as fuel cell and electrolysis making them attractive for systems with high share of fluctuating renewables but also improving the investment into plants with two functions. In general, there is a need to commercialize SOECs and improve the operation hours and degradation rates of electrolysis for all technologies. It is therefore important to prioritize the already available technologies on the market with alkaline being the most matured one and PEM as an emerging one, while SOECs should be introduced. Moreover, the synergies in the fuel production chain and the maturity of some technologies, such as biomass gasification, needs to be investigated in a system configuration for fuel production.

The primary focus of electrolysis demonstrations in Denmark is biogas upgrade with electrolytic hydrogen and hydrogen as end fuel with potential for providing ancillary service. Denmark has a strong focus on all three leading electrolysis technologies (alkaline, PEM and SOECs) and has local producers and research focused development activities. There are no immediate barriers to start this necessary transition of our energy system, but there are also no clear incentives to do so as well. There is a need to establish electrolysis as an interesting business opportunity, create relevant framework conditions and a market for its penetration and proceed with implementation of the available technologies on the market.

Denmark has been a green hub of Europe for many years, with a strong focus on renewable energy and incentives for their implementation. Denmark has also profiled itself as a world leader in wind energy and economic growth was sustained partly due to the local wind industry. More precisely 74.1% of the employment related to renewable energy is related to wind energy [15]. Moreover, due to the high share of wind in the Danish electricity production, Denmark is a suitable location for real-life demonstration. Due to the nature of its electricity sector, it can be utilised to predict the potential issues and problems that may occur with the integration of renewable energy and the lessons can be shared with other countries in the future.

With the increasing penetration of renewable energy in the electricity grid, Denmark could help set the agenda for the future energy system transition for the transport sector, since there are many domestic opportunities regarding the technologies involved and stakeholders. Denmark has local technology producers for electrolysers and catalysts/chemical synthesis. It has experience with a high share of renewable electricity, which makes it a perfect test location for different integration technologies. It has experience with balancing issues and integration of renewable electricity production and the energy transition away from fossil fuels has already started. Investments in electrolysers, fuel production facilities and niche markets demonstrate a good opportunity to boost local jobs. Research capacity in the field is available and it can support this transition, such as the development of solid oxide electrolysers, investigation of combustion engines running on methanol, and the integration of electrolysers with electricity grid.

The set of activities that are the most suitable for transforming the transport sector within the renewable energy system transition are presented below. Firstly, an overview of the technology readiness levels (TRL)[1] for the fuel production pathways are presented. This short overview should give insights of the technology status of the most important components for the P2G and P2L concepts.

The activities are grouped according to their focus and are based on the foreseen steps needed to reach the implementation of electrolysis and its applications in the energy system. The roadmap is divided into four main stages, which are illustrated in Figure 2:

- *Market preparation* - now to 2020
- *Market uptake* - period from 2020 to 2025
- *Market implementation* - period from 2025 to 2035
- *Large-scale implementation in smart energy system* – from 2035 and onwards

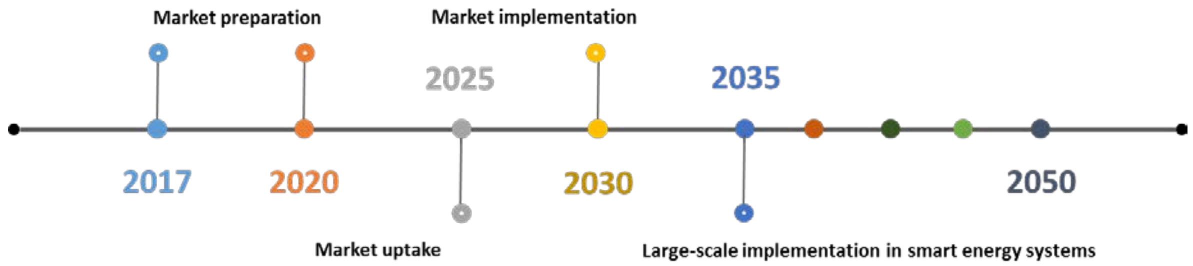

Figure 2. Roadmap for electrolysis systems from now to 2050

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[1] Technology readiness level is defined according to European Commission

Overview of technologies and their development stage

There are different ways to use electrolysis, as previously indicated, and the following section will focus on the power-to-gas and power-to-liquid pathways. The maturity of the individual technologies in the fuel production pathways is more advanced than generally presumed, but the concept as an integrated production system remains to be proven on a larger scale. Most of the technologies that serve as individual components in the systems are on different technology readiness level (TRL) therefore Figure 3 illustrates the indicative status of the technologies for the three concepts that are seen as the most promising for solving the issues in the transport sector.

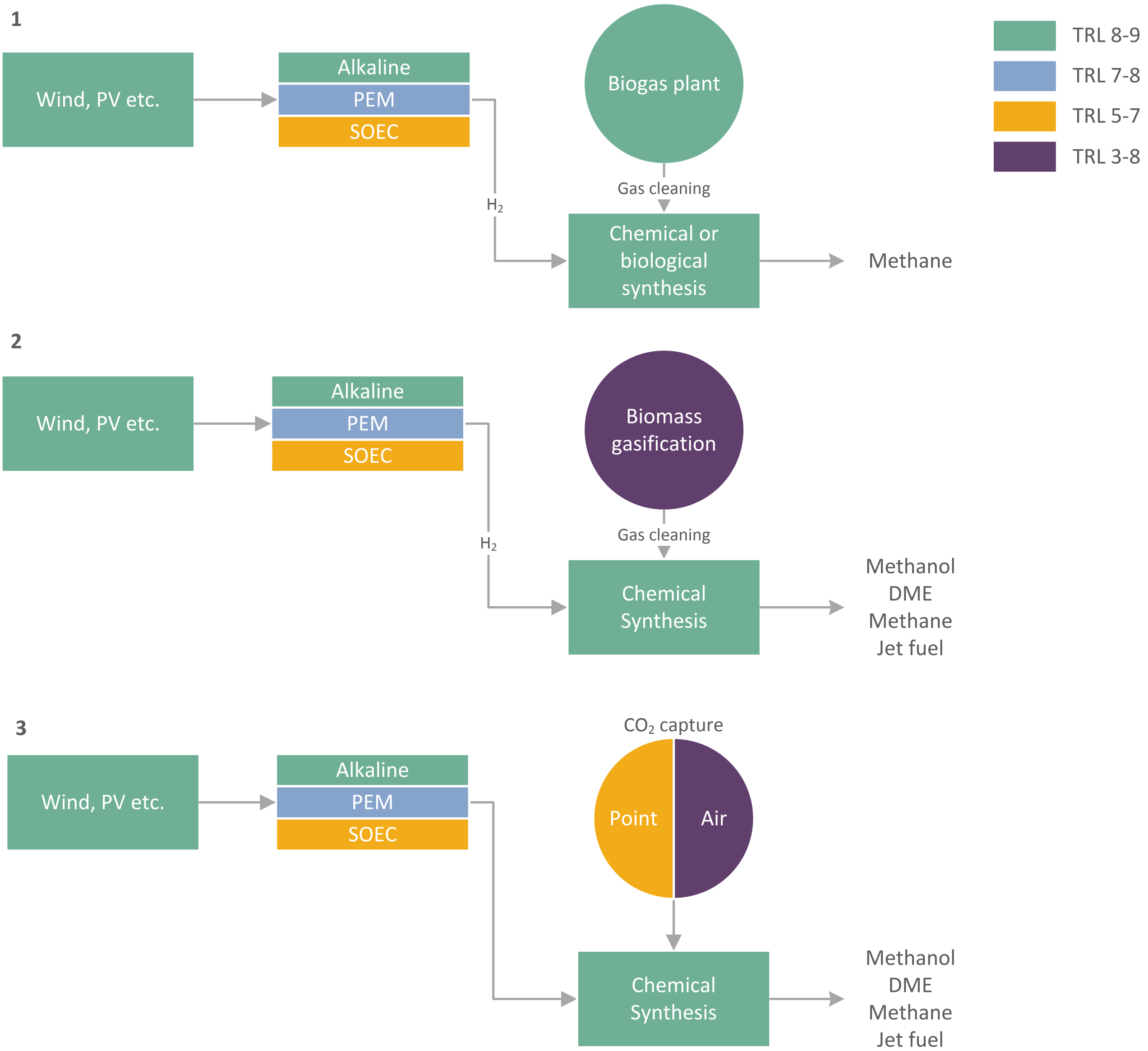


Figure 3. Power to fuel conversion processes with indicative technology readiness levels: 1) biogas upgrade with electrolysis, 2) biomass hydrogenation and 3) CO2 hydrogenation to desired fuel products

Out of three main electrolysis types, alkaline has been present the longest on the market and is largely used in industry (TRL 9) with capacities up to 100 MW scale. PEM electrolysis has been emerging on the market in the last decade (TRL 7) and is currently available on single-digit MW range, while the solid oxide electrolysis cell is still at the development level (TRL 5) with kW size prototypes being tested both in Denmark and in Germany in the desired concepts [9,16]. PEM electrolysis is available in single digit MW scale, while SOECs are on the kW level.

Biogas plants are fully commercialized technologies (TRL 9) with 21 centralized plants in Denmark and 45 farm scale plants [17], while biogas upgrade with hydrogen is on the border of mature technology (TRL 7-8) according to [18]. Concept 1 (Figure 3) has been demonstrated in Denmark [16,19]. This concept can also be expanded to production of liquid fuels, however this could lead to additional energy losses and consequently lower fuel outputs. Biomass gasification still has a wide range of the technology readiness level due to the many components that are part of the gasification system and different types of gasifiers (TRL 3-8). Denmark has successfully demonstrated Pyroneer technology at 6 MW, which was capable of running on different types of biomass, however the project was closed down and no further plans were reported since 2014 [20]. The biomass hydrogenation pathway (Concept 2) has not been tested in Denmark nor in other countries to the author's best knowledge. Gasification of biomass followed by methanation, without addition of hydrogen was tested under GoBiGas project in Gothenburg [21]. Different types of biomass can be used as a fuel source for gasification, where it is considered that in Denmark straw could have a big role in the fuel production via this technology. Biogas plants strive to operate at highest possible dry matter content, therefore, it can be assumed that straw share will be increased in the future biogas plants.

In the short-term carbon dioxide capturing can be achieved through point source carbon capturing either from power plants or industrial plants, or in the future by extraction from air. The first pilot plant for CO_2 capturing from stationary plant was inaugurated in 2006 in Denmark as a part of CASTOR project [22]. In 2014, there were 22 plants around the world, 9 in construction and 13 operating, that have installed carbon capture technology. Three plants out of 22 were capturing carbon from power plants in Canada and USA, while rest are industrial plants [23]. Note that all of these plants are carbon capture and storage plants, which is not the objective of the pathways suggested in this report but rather carbon capture and recycling. In the case of concentrated point source capturing, post and pre-combustion capture is still at the demonstration level (TRL 5-7). Most of the air capture technologies are still at the prototype scale (3-4) [24]. It is reported that electro-dialysis and temperature swing absorption are both on TRL 6 [25]. According to Pérez-Fortes *et al.* [26] it can be concluded that the Concept 3 is on TRL 6-7 due to the two plants that have tested the concept [8,9]. In the future, if SOECs reach a desired technological level, co-electrolysis of CO_2 and H_2O could be a possibility, which will be additional option for Concept 3, where desired fuel product would be methanol due to syngas output that is a mixture of CO and H_2.

Heavy-duty transport fuels for ship and trucks should have priority, as the potential for completely electrifying these end uses is unlikely. Another part of the transport sectors that deserves attention is aviation. Here the energy efficiency can be significantly improved, however future growth in air traffic is very likely and the efficiency gains will not fully eliminate the increase in the fuel demand. In this roadmap using electrolyses as a potential part of solving the challenges in aviation is included, as finding a solution for jet fuel production is very important on a global scale. Jet fuel production can be done via the concepts presented above, finishing with chemical synthesis (TRL 9) either by Fischer-Tropsch (FT) technology or via the methanol route. Aviation fuels have very high restrictions for technical approvals, and any alternative fuels not produced by FT technology today will not be approved for use. Methanol and DME are not suitable fuels for aviation, therefore these need to be further converted into jet fuels via the olefin synthesis, involving oligomerization and hydrotreating [25]. FT synthesis is commercialized on a large scale, however the small-scale FT synthesis has TRL 5-6 [18]. This causes an issue due to the currently smaller scale of other components in the chain. Integrated P2L jet fuel production with reverse water-gas-shift has only been realized at research level, while general TRL for P2L is 5-8 according to [25]. It is important to note that the production of jet fuels will result in different by-products produced in the chain, such as gasoline and diesel, which can be used for road transport.

Phase 1: Market preparation - from now to 2020

The current long-term planning is missing clarity and there is a need for consistency in the energy visions. A clear strategy about how to move progress is needed, and this will enable more attention to be placed on certain key technologies and put them on the agenda. Many regulative measures related to renewable energy targets finish at year 2020; hence, investors are very conservative in their support for new technologies that are not part of the governmental plans. They mostly support currently recognized technologies. Both academia and government can evaluate the need for these technologies and initiate targeted programmes, education and investments. It is important that the regulation recognizes the sustainability benefits of fuels produced via electrolysis since they have a low land demand, low water demand and can eventually be CO_2 neutral if the carbon is captured from the atmosphere. None of the other alternative renewable fuels possess these characteristics.

During the market preparation period, the goal is to develop demonstration units of electrolysers and integrate them in the production plants with installed ***electrolyser capacity of 1-3 MW_{el} per plant***. With total installed capacity in the range of ***7 and 10 MW (3 to 5 plants)***. Primary focus is on alkaline and PEM electrolysers as commercialized options, with transition towards SOECs when they reach desired technological level. New demonstration projects should focus on scaling up the low electrolyser capacities in the current demonstration units.

ACTIVITIES RELATED TO DEMONSTRATION AND PLACEMENT OF THE PLANTS

- **Demonstration of power-to-gas and power-to-liquid systems**
  More demonstration projects are needed to test the systems, improve the business cases, gain experiences with the technology and to create greater awareness in the public. Demonstration projects can also support the needed knowledge transfer, eliminate operating problems and encourage the needed developments for better operation within the energy system. Different configurations need to be tested to maximize the synergies and flexibility, and to create new revenue streams such as district heating supply.

  Electrolysis based technologies to be demonstrated:

  - Biogas upgrade with electrolysis to gas and liquid fuel
  - Concentrated point CO_2 sources (e.g. power plants or industrial plants) with electrolysis to liquid and gas fuel
  - Biomass gasification with addition of electrolytic hydrogen to liquid fuels

  The demonstrations should be based on the already commercialized electrolyser technologies alkaline and PEM, while pilot plants should be tested with SOECs. The focus of the demonstration should be to provide the fuels for the heavy-duty road transport or marine fuels. As a part of the market redesign described later on, pilots and demonstration plants could be established in a tendering process with e.g.

30% investments subsidy for the whole system (not just the electrolyses plant). The demonstration plants could be larger than listed, but in any case, the demonstration plants should include the collection of technologies and not just the electrolyses plant.

- **Placement of plants that enables future connection to electricity, heat and gas networks**
  Specific locations that have best connections to grids need to be identified, since this will be an important factor to minimize the costs of new grid establishments. The locations should be identified on the municipal level, as this approach had been successful in defining areas for wind turbines and biogas plants. The plant placement also needs to take into consideration end-use needs, fuelling infrastructure and resources needed as well as the proximity to wind power, to make efficient use of existing or new electricity transmission grids. The fuel production plants have excess heat production, therefore placement close to the district heating network would be desirable, as well as placement close to the gas network if the final products can be injected into the existing gas grid.

- **Consider flexible operation to accommodate renewables**
  The operation of plants needs to be aligned with renewable energy production in the system, therefore constant operation should not be prioritized nor should capacity of the plants be in alignment with constant operation mode. This ensures that electrolysers can maximize the integration and use excess production of renewable electricity that will occur in the system once the wind capacity is further increased. There has already been days when the Danish energy system was operated by using electricity from wind, solar and CHP plants and without central power plants. This is expected to occur more often in the future therefore choosing the right installed capacity for electrolysis will be important in order to help the integration of intermittent electricity in the system.

REGULATORY MEASURES AND ADDITIONAL INCENTIVES

- **Market design for electrolysis implementation**
  In order to introduce the electrolysers on the market where it will compete with established and cheaper technologies, it is important to create special market conditions. The construction and design of market conditions for this new energy infrastructure and technology is essential in order to achieve the competitiveness. Gaseous and liquid fuels that are produced from electrolysis cannot and should not to be seen as competitors to established fossil fuels such as natural gas, diesel or petrol but as a part of a new market of renewable transport fuels. The electrofuels will be competing with electric vehicles, bioethanol and other types of biofuels. It is clear from past experience that the current framework is not adapted to technologies that bridge electricity to transport/gas/liquids. The current risks of even investing should be reduced. In the period until 2020 new targeted market conditions for electrolyses should be tested and could be limited to a capacity between 7 and 10 MW or 3-5 plants which receive a subsidy of e.g. 30% of the investments. It is equally important to ensure that these are operated in a way that could test future market conditions. The principles in the market conditions should take into account:

    - proximity to electricity from renewables (to limit the need for expanding distribution and/or transmission grids),
    - proximity to district heating (to enable use of waste heat) and
    - proximity to gas grids (if relevant).

An innovative market design should also consider, that such plants should preferably not operate 100%, but be able to stop at times when prices are high (wind resources are low). This will enable a higher utilisation rate of fluctuating renewable energy. Previous analysis [27] shows that a 50% operation time is a good indication for how the markets for electrolyses should be designed in order to increase the utilisation of wind power. This is crucial to reduce the costs of the overall system, as this:

- can enable lower use of power plants and CHP plants and increase use of low cost wind power
- contributes to significantly increasing the technically possible wind power share in the total energy system
- can reduce the longer term investment costs in the distribution and transmission grids if also placed close to wind power (MW electricity can go from wind power to electrolyses instead of having to be transported to end consumers via new or existing transmission and distributions grids)

In Figure 4 the current electricity prices are illustrated together with the anticipated costs in 2022. We suggest to construct a limited market for 7-10 MW which can take into account the benefits of operation the electrolyses plants at times with “low congestion” in the electricity grids. Figure 4 shows the principle scheme in which:

- the contribution to the DSO and TSO should be adjusted according to the time of operation and location of the electrolyses plant, i.e. assuming that in the future such operation can lower the marginal expansion costs of the grid if plants are placed in proximity to renewable energy production centres.
- or replace the contribution to DSO and TSO with own investments in grid connection to renewable energy production, e.g. a wind power park, however with some demands to share the connection and in compliance with rules formulated by the TSO and the relevant authorities.
- the payment for electricity is based on the principle that most of the electricity can be used from concrete wind power plants and should hence be based on “real” costs i.e. both the long-term investment costs and short-term costs (LCOE) in renewable energy plants as well as grids.

This means that according to Figure 4, the lowest price would be for onshore wind turbines plus the system tariff (balancing and regulation) plus the electric grid connection (DSO/TSO tariff or own connection costs). The electric grid connection costs can be very low depending on the proximity and ability to operate in accordance with renewable energy production. The highest costs illustrated are offshore wind combined with the current average DSO and TSO costs. The principle is that e.g. large electrolyses plants can be placed near large offshore or onshore production. For the overall economy of the electrolyses plant the placement near gas grids, gas storages, district heating can be pivotal as well as the end use of hydrogen for e.g. electrofuels.

The concrete condition for amendment of the contribution to the DSO and TSO as well as the design of a marginal price approach to payment for the DSO and TSO should be constructed in a collaboration with Energinet.dk and other relevant authorities. The idea however is, that certain principles could be tested until 2020. In the next phase until 2025 more plants can be demonstrated or new support schemes and market conditions can be tested. As part of the demonstration plant the tender should ensure, that the fuels are used in blends in the transport sectors.

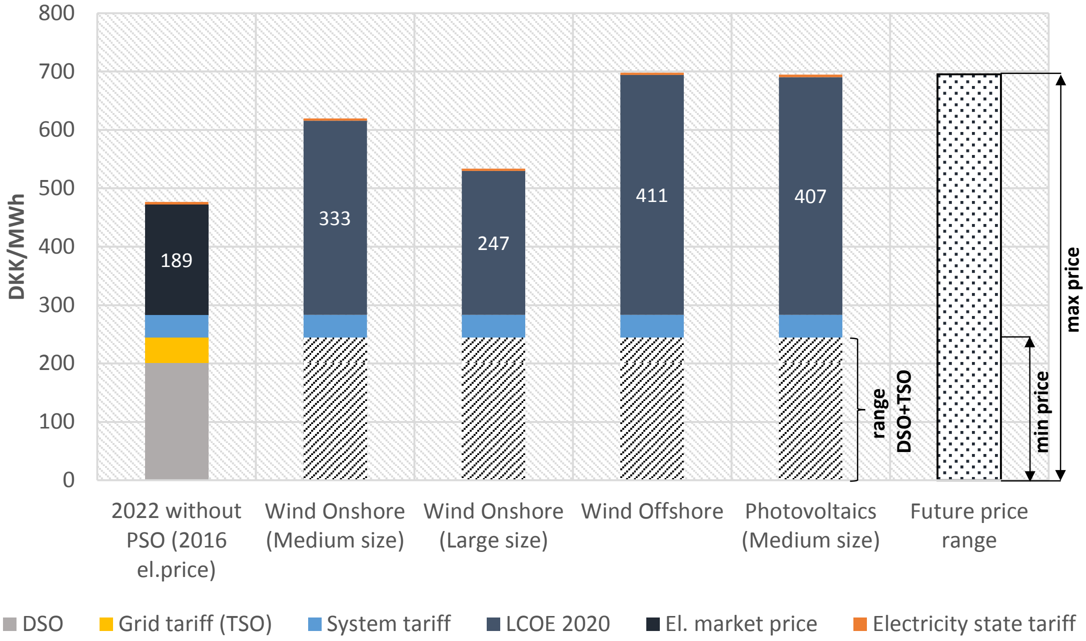


Figure 4. Scheme suggestion for different renewable energy sources and their LCOE, together with anticipated costs for 2022 when PSO tariff is removed (el.market price for 2016)

- **Niche gas markets and hydrogen as end fuel**
  The establishment of electrolysis in the specialized gas markets will enable the introduction of the technology to the energy system and opportunities for testing the operation conditions. Hydrogen as an end fuel already has a supportive scheme in EU legislation and initiatives for establishing infrastructure are in place, therefore this can be used as a good market entry for electrolytic hydrogen and more complex fuel systems. Moreover, the establishment of a specialized gas market will be an entry point for industrial use of electrolysis.

- **New blend standards acknowledgement**
  Currently the blend standards recognize methanol and DME as oxygenates for petrol, with blends up to maximum of 3% and 22% of the total volume respectively [28]. The same blend allowance is from 1985. However, the blends are not obligatory as they are for ethanol blends so they do not support the use of these fuels. Modern petrol vehicles can run on methanol blends as high as 15 volume percent [29]. Long term planning should ensure that electrofuels (primarily methanol and DME) are acknowledged in the legislation by promoting blend standards that encourage the low biomass intensive fuels and/or recycled carbon fuels. Denmark should promote these changes on the European level because the top-down approach is causing the limitation in this specific regulation. Amendments made to Renewable Energy Directive and Fuel Quality Directive, finally recognized renewable liquid and gaseous transport fuels of non-biological origin, which includes fuels from P2G and P2L technologies and they should be included in the calculation of the renewable energy for transport and greenhouse gas emission savings [30].

  It is technically proven and being demonstrated that vehicles can run on high-mix blends of methanol and 100% pure methanol and DME. The concerns related to using the higher blends, due to the current car standards, is understandable. However, the exclusion of these fuels on the market prohibits the creation on the market of vehicles that can use these fuels or for modifications of the existing vehicles, similar to the modifications of petrol combustion engine to run on LPG and simultaneously the creation of needed infrastructure.

- **Establishment of knowledge centre**
  In order to establish a better communication between the industrial producers of the electrolyser technology and the researchers a knowledge centre for electrolysis should be established. It should be based on the production units and implementation of electrolysis for advanced transport fuels (electrofuels). There are demonstration units in Denmark and around Europe and in order to avoid duplicate demonstrations, experiences should be shared which will help accelerate technology development and market entry. Existing partnerships in Denmark could be connected such as "Partnerskabet for brint og brændselsceller" and "Partnerskabet for Termisk Forgasning". By reducing the gap between academia and industry, the very important goal to promote the innovation and investments in energy transition can be achieved. The knowledge centre is also important in order to have a communication channel between investments in electrolysis and the changes in the whole energy system, as this specific technology offers a potential for renewable energy integration and forms a link between two sectors – electricity and transport.

TECHNOLOGY IMPROVEMENTS AND RESEARCH MEASURES

- **Research and development activities**
  There are many different technology configurations in power-to-gas and power-to-liquid plants depending on the resources used and desired product. The relevant technologies are at different stages of their technology life cycles, so the needed activities will vary. Here the most relevant technologies are mentioned. Solid oxide electrolysers need to reach higher development stages and potentially commercialization in the next 10 years. Therefore, more research activities are important in the improvement of the durability of the cells, and the performance and integration into energy system. Further development of biomass gasifiers is needed, including the reestablishment of the successful Danish Pyroneer technology and up scaling should be supported since the future energy system needs to maximise the use of non-homogeneous residual biomass. Carbon capturing from stationary sources is a technology in demonstration, but further investigation on the capturing of carbon from air is needed and up scaling currently developed concepts is non-existent today. One of the largest challenges with decarbonising transportation fuels is finding a renewable fuel option for aviation. There is a lack of technically feasible alternatives with current options demanding a large amount of biomass and water and these alternatives are at a similar development stage. Therefore, it is believed that Denmark should intensify its research on jet fuel production via electrolysis, since this could make it a front-runner on the global market.

  Focal technologies:
    - Solid oxide electrolysis cells
    - Biomass gasification (Pyroneer and Viking)
    - Carbon capturing from stationary sources and air capturing
    - Aviation fuels from P2L

- **Fleet testing**

To generate knowledge on the vehicle performance and efficiency with different driving cycles testing engines and vehicles running on alternative fuels is important. The produced fuels can vary from gas to liquid ones, therefore it is also important to test their use for marine and aviation transportation where alternatives are missing. This can be both done by research institutions and by doing field tests of existing vehicles on the market. Experiences can be learned and collaborations can be made with countries currently undertaking research on these fuels. In Iceland, there is currently a fleet test of methanol vehicles, and in Sweden VOLVO manufactured heavy-duty trucks are running on DME [31,32]. Stena Germanica has been converting ferry engines to methanol, testing three engines able to run fully on methanol [33]. DME vehicles require special tank, but conversion of diesel vehicles to DME fuel have been successfully done by VOLVO.

Small fleet test in Denmark should be initiated in collaboration with a company or one of the municipalities, where 10 internal combustion engines vehicles should be tested on DME and one passenger ferry conversion to methanol should be initiated and tested in the period up to 2025.

Phase 2: Market uptake – from 2020 to 2025

The market uptake phase is very important, since it will create more visibility for the technology and attract investors if the previous steps are successfully carried out. In this period, the goal is to scale up the electrolyser demonstration units to a the larger MW scale. Ranging from ***5 to 20 MW$_{el}$ per plant***, with total installed capacity in the ***30 to 50 MW range***, which would correspond with the target of ***5 to 10 electrolysis based plants***.

It is expected that this is technically possible with commercialized electrolyser technologies because alkaline has already reached three-digit MW scale. The main barrier in practice would be the investment expenses. The business cases can be improved by changes in regulatory measures that should be introduced in the first phase of the roadmap.

ACTIVITIES RELATED TO DEMONSTRATION AND PLACEMENT OF THE PLANTS

- **Upscaling the demonstration units**
  For the upscaling step that should occur in this period, it is essential that the demonstration in the previous stage is successful. Upscaling is particularly important since it can demonstrate the numerous potential issues with the technology. Furthermore, it can reduce the prices and improve the efficiencies of the processes. The upscaling can happen in a relatively short period of time once it is initiated. Most technologies in production cycle are favourable of large-scale plants, so eventually economy of scale will occur. This stage needs financial support. Hellsmark and Jacobsson looked into the required investments for biomass gasification in order to contribute to the fuel production market and the results show that the investments are €60–120 billion for EU [34]. Once the demonstration plants have proven feasible, the next step would be to continue up scaling and make a strategy for the founding commercial plants.

- **Establishment/adaptation of fuelling infrastructure followed with fleet expansion and road testing**
  Large–scale road fleet testing and fleet expansion with higher percentage blends of petrol with methanol should be initiated. DME should be implemented as pure fuel in the dedicated or adapted diesel engines. This could be funded by projects or be done when companies change their fleets and they want to generate green profile. Fuelling infrastructure needs to be established at the same time. Hydrogen

refuelling stations are already in place in Denmark and there are EU supports for the expansion of infrastructure. In order to establish a functioning infrastructure with the sufficient amount of refuelling points, adaptation of existing fuelling stations and installation of refuelling stations for other fuels such as methanol and DME should follow the fleet expansion. One methanol refuelling station is in place in Denmark but no existing stations are adapted to methanol or DME. DME has similar properties as propane so the market available technology can be used for this fuel. By establishing this infrastructure it will provide a good foundation to expand the vehicle and renewable transport fuels market.

- **Pilot scale testing of jet fuel production**
  If research on jet fuel production is intensified in the first stage, pilot scale testing of jet fuel production via electrolysis can be initiated. The objective should be to develop the integrated fuel conversion facilities that can be up-scaled, since the long-term demand of jet fuels needs to be supplied with alternative fuels. The pilot testing of the production facilities needs to be accompanied with testing of the produced fuels in the aircraft engine to complete fuel property requirements and performances. The establishment of a consistent database of the engine performances and fuel production cycles should be initiated to better monitor the feasibility of technology. An evaluation of the development needs and needed resources for training of personnel should take place.

- **Placement of plants as part of the decision making**
  During the upscaling of the production plants, the location and system integration should be considered. This involves identifying access to carbon sources, biomass/biogas sources and existing electricity, gas, district heating networks depending on the plant type. The placement of electrolysis units close to the renewable electricity producers is preferred instead of expanding the existing grids. The transportation of final fuel products is already being done in the today’s system and this is considered a non-issue.

REGULATORY MEASURES AND ADDITIONAL INCENTIVES

- **Electrolysis as fundamental technology in smart energy system**
  The policy framework plays a key role in the development of the technology. Creating stable market conditions can encourage investments and large-scale demonstration. Electrolysis needs to be recognized as a fundamental technology for the smart energy system in the long-term energy vision. A market design is needed that will enable harvesting of low renewable energy prices, in order to allow that the operation of the fuel production plants is flexible and they follow the production of renewable electricity, to avoid grid expansion and grid stability issues. Electrolyser capacity needs to ensure that the utilisation of the low price renewable energy will be maximized and it provides the needed flexibility to the system. The market design scheme tested in the initial phase until 2020 should be elaborated and possibly adjusted according to the experiences. The principles listed in the provisos period should be taken into consideration when establishing a market for the 30-50 MW plants. Concrete investment subsidies may still be necessary for the SOEC technology to get closer to actual commercialisation, while this should not be necessary for PEM and alkaline electrolyses.

- **Market establishment of fuel sales**
  It is important to establish the fuel sale market in order to break a present vicious circle. If the investments in the infrastructure are not there because there are not enough vehicles to use it, and vehicles manufactures are not selling cars at competitive prices to conventional ones because there is no

demand from the customer side from it. The customers are not in favour of buying vehicles because infrastructure is not in place or not spread around the country, so it enables the normal driving ranges. A selection of cities could be used for piloting electrofuel mobility, with a favourable fuel-tax regime that relates these electrofuels to other alternative fuels. Raising public awareness about the safety of the new fuels on the market supported by conversion programmes (together with infrastructure changes) can boost the sales on the fuel market and the need for vehicles.

TECHNOLOGY IMPROVEMENTS AND RESEARCH MEASURES

- **Continuation of research activities from previous stage**
  The continuation of the research initiatives is important to achieve the best technology development. In addition, focus should be placed on biomass gasification, SOECs, CO_2 air capture and jet fuel production. Looking into the complexity of the gas grid should be prioritized. This is important since the gas grid in the future will not necessarily have the same role as in today's system and there is a possibility that different gas grids develop and these will facilitate the implementation of electrolysis and electrofuels in the system.

Phase 3 and Phase 4: Market implementation – from 2025 to 2035 and Large scale implementation in smart energy systems – from 2035 onwards

In the period up to 2035, it is expected that both the refuelling infrastructure is in place and that fleet tests have proven successful. This provides an opportunity to improve and expand the vehicle market. Furthermore, this can be accompanied by expanding the blend standards, availability of different fuel blends on the market, and at a few locations pure DME and/or methanol for dedicated vehicles will be accessible. This phase is also aligned with up scaling of the production facilities and electrolysis itself. It is expected that the ***electrolyser capacities are bigger than 50 MW*** and that there could be a total of ***1000 MW of electrolysis*** integrated in the system. After 2035, the main focus is on the implementation of the technology as an active part of the smart energy system to maximize the integration of renewables and flexibility in the system. The concrete market design and conditions should be based on the experiences in the demonstration plants. A continued effort to bring the SOEC from a pilot stage to commercialisation is most likely necessary.

ACTIVITIES RELATED TO DEMONSTRATION AND PLACEMENT OF THE PLANTS

- **Upscaling the jet fuel production via electrolysis**
  Depending on the readiness of the technology at this stage, the upscaling of pilot scale testing to demonstration units should be initiated. The use of the produced fuel for the smaller aircraft fleets can be done in collaboration with interested companies, which could encourage the other actors to join. The further deployment of this technology should continue since this is currently the only alternative that has very low water intensity and land use impact.

- **Start pilots of needed grids and storages (liquid fuels, temporary hydrogen)**
  With higher production capacity in the system, it is important to investigate the additional infrastructure that needs to be put in place to maximize the synergies and the flexibility of the system. Depending on the outcome of the gas grid analysis, pilot testing of new grids or gas injection to the existing grid needs to be initiated. This should be aligned with the plant location and existing infrastructure in the system.

Moreover, since the use of electrolysis for fuel production enables seasonal storage, the required storage capacities and demonstrations of integrated solutions are important.

1. Technology status and potential utilisation purposes

In the 1890s, the Danish inventor Poul la Cour, known as the wind mill pioneer connected an electrolysis unit directly with the electricity from wind power producing up to 1000 litres of hydrogen and 500 litres of oxygen per hour on a windy day [35]. A long history of Danish involvement in electrolysis is evident today with the producers representing the most known electrolyser technologies. The electrolyser technologies are divided by their type of electrolyte: *alkaline electrolysers* use liquid and *polymer exchange membrane (PEM)* and *solid oxide electrolysis cell (SOEC)* electrolysers use a solid electrolyte. Alkaline electrolysis has been available for almost 100 years and is the longest existing commercialized technology, followed by PEM which reached its commercial status in the last decade. The most recently available technology on the market is the anion exchange membrane (AEM). SOECs are not currently available in commercial form but have been successfully demonstrated. The historical development of electrolysis is illustrated in Figure 5.

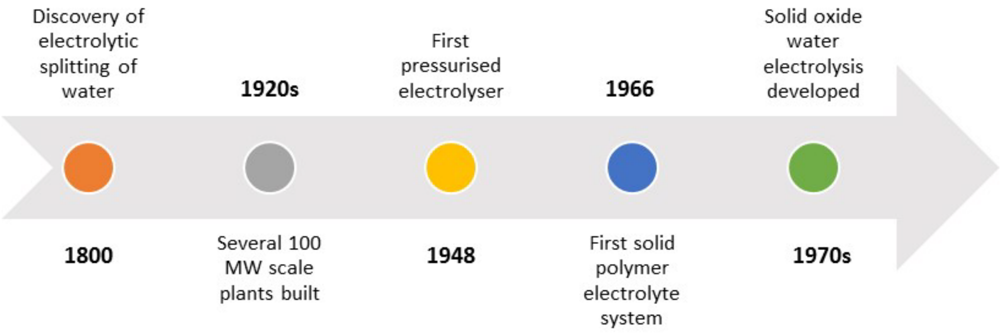


Figure 5. Historical development of electrolysis. Adapted from [36]

Alkaline electrolysis is a mature technology. Traditional alkaline electrolysis operates at atmospheric pressure and it is designed for stationary grid-connected operation, but there are also pressurized alkaline electrolysers that have a much faster response time down to 1-3 s [37]. The 1920s were known as “golden age” of alkaline electrolysis where several plants were built at 100 MW scale. The biggest realized project with 162 MW was built in the 1960s in Aswan Egypt and other projects from this period were decommissioned in the 1980s [38]. Alkaline electrolysers have long lifetimes with up to 30 years of operation including the general replacement of electrodes every 7-15 years [2]. Alkaline water electrolysis has regained attention recently as it can use non-precious metals as catalysts and can have different setups [39]. Furthermore, the spectrum of materials that can be used is much broader in comparison to PEM electrolysis since both noble and non-noble catalysts can be used. Alkaline electrolysers have three major issues: 1) low partial load range, 2) low operating pressure and 3) limited current density [40]. In comparison with other electrolysis technologies the purity of the gas output by using conventional alkaline electrolysers is rather low but with advanced high temperature alkaline the purity of the hydrogen can reach 99.9 vol.% [2]. The standard operation temperature range for cells is 60-80°C, but experiments were conducted with high temperatures of up to 400°C [41]. The efficiency of the alkaline electrolysers are similar to PEM, but they are characterized by low current densities.

The oil crisis in the 1970s regained the interest in electrolysis. The first polymer exchange membrane was developed in 1966, and small scale PEM for military and space purposes appeared in the 1970s [36]. PEM has been emerging on the market during the last decade. In 2015, Siemens installed a 6 MW PEM system consisting of three 2 MW electrolysers in Germany, making it the largest PEM electrolyser in the world [42]. In 2014, Siemens announced together with Blue Fuel Energy to install a 20 MW PEM system with 1.25 MW each, however no updates were reported on this project [43]. In 2017, the HyBalance project will install a 1 MW PEM electrolysis unit able to generate 230 Nm^3/h of hydrogen for transport and ancillary services [44]. Operating temperatures for commercialized PEM electrolysers is between 65-85°C [45]. The reported lifetime for PEM electrolysers is 5 or more years [46]. PEM electrolysis has a more compact system design, high voltage efficiency and produces high purity gas [36]. It is also more suitable for rapid response and can work under a wide range of power inputs [40]. One of the issues with PEM is their use of noble metals (platinum group metals) resulting in high costs for components and in the long-term potential problems with resource scarcity. The capital costs are a large obstacle for PEM implementation at the current stage.

Being developed in the 1970s, steam electrolysis by using solid oxide electrolysis cell (SOEC) had the first experimental results in the 1980s [40]. By operating electrolysers on high temperatures between 800 and 1000°C results in higher efficiency in comparison to other electrolyser technologies [47]. Even though they are not currently commercialized, they have been demonstrated and are gaining more attention due to their specifications. SOECs are conducting oxide ions, enabling carbon dioxide electrolysis and a combined H_2O and CO_2 electrolysis known as the co-electrolysis. These processes are not possible with PEM and alkaline electrolysis. Furthermore, the materials used are relatively cheap in comparison to other electrolysers, since SOECs use a ceramic electrolyte. Solid oxide cells can also carry out reversible operation, meaning they can operate both in fuel cell and electrolysis mode, more known as reversible solid oxide fuel cell (RSOFC). This makes them very attractive for systems with fluctuating power production but it also improves the business economy of the plant since it offers two functions. One of the biggest challenges with SOECs is the durability of the cells and that their lifetime is short in its current stage of development. Moreover, balance of the plant component at high operating temperatures is also a challenging factor. However, there are demonstration projects that show successful application of this technology, but in comparison to other technologies, they are still on the kW level. The SOPHIA projects are doing proof-of-concept tests on the integration of concentrated solar energy source and a pressurized 3 kW SOEC [48]. The ECo project that started in May 2016, will demonstrate the co-electrolysis process of simultaneous electrolysis of steam and CO_2 during the project period of 3 years [49]. A few new demonstration projects in Denmark and Germany were announced for the next year for ~30 kW size [45].

Latest demonstration projects in Denmark:

- ***1 MW alkaline for power-to-gas via biological catalysis***
- ***1 MW PEM for ancillary service, industry and transport***
- ***40 kW SOEC for biogas upgrade***

Table 1 provides an overview of the manufacturers of electrolysis technology in both Europe and USA. There are a lot of manufacturers and electrolysis activities in the EU for all types of electrolysers. An extensive study focused on the development of electrolysis in the EU was done in 2014 [5]. It reported that electrolysers will be used within energy application with expected cost reductions and improvements of performance of electrolysers.

Table 1. List of identified electrolysis suppliers

Electrolysis type	Producer	Country
AEM	Acta S.p.a	Italy
Alkaline	GreenHydrogen.dk	Denmark
Alkaline	ELT Elektrolyse Technik	Germany
Alkaline	McPhy	Germany
Alkaline	Wasserelektrolyse	Germany
Alkaline	Erredue s.r.l	Italy
Alkaline	H2 Nitidor	Italy
Alkaline	Idroenergy	Italy
Alkaline	NEL Hydrogen	Norway
Alkaline	IHT Industrie Haute Technologie	Switzerland
Alkaline	PURE Energy Centre	UK
Alkaline	Teledyne Energy Systems	USA
Alkaline, PEM	Hydrogenics	Belgium, Canada
Alkaline, PEM	SyGasTec GmbH	Germany
Alkaline, SOEC	Toshiba	Japan
PEM	IRD A/S	Denmark
PEM	AREVA	France
PEM	CETH2	France
PEM	H-TEC SYSTEMS	Germany
PEM	Siemens	Germany
PEM	H2 agentur/Giner	Germany, USA
PEM	Shinko Pantec	Japan
PEM	ITM Power	UK
PEM	Wellman-CJB	UK
PEM	LYNNTECH	USA
PEM	Proton OnSite	USA
PEM	Hamilton Sundstrand	USA
SOEC	Haldor Topsoe	Denmark
SOEC	Sunfire	Germany
SOEC	SOLIDpower	Italy
SOEC	Ceramatec	USA

**the list is not an exhaustive list and it is based on the authors best knowledge and available data*

Apart from the previously mentioned electrolysis demonstrations, many other demonstration projects are related to the power-to-gas or power-to-liquid concept. Being a leader in the EU, Germany is investing 57.2 M€ in power-to-gas technology [50] and had 17 pilot and demonstration projects in the last 10 years. The first pilot project on power-to-methane was launched in Germany in 2009 and the most projects were in 2012 [51]. Most EU countries are focusing on using electrolysis for hydrogen production but Germany and Denmark are leading with demonstrations of electrolysis for gas and liquid fuel purposes. There are currently seven ongoing demonstration projects in Denmark that have been identified and three have field demonstration on a larger scale. The BioCat project uses hydrogen from alkaline electrolysis for biological methanation and the first methane was produced in April, 2016 [52]. The SOEC technology has been tested for six months in the Foulum project, where hydrogen produced from electrolysis is used for upgrading CO_2 from biogas [16]. Bailera et al. provides a detailed list of power-to-gas projects from 2010 to today [53].

There are two power-to-liquid plants: 1) the George Olah plant in Iceland, which produces methanol from CO_2 and hydrogen from alkaline electrolysis [8], and 2) a plant in Dresden, which produces diesel from CO_2 and H_2 [9]. The latter one was the first one to demonstrate SOECs for fuel production purposes. The same company, Sunfire, is planning to develop a pressurized 200 kW stack that will be suitable for the integration with a methanation reactor and power-to-liquid applications [51]. A new emission-to-liquid project started at the Lünen coal power plant in January 2015 where CO_2 emissions from coal power plant will be converted with hydrogen to methanol, it is expected that the plant will start its operation in 2017 [10]. The newest power-to-liquid project was announced in the Swedish Luleå's steel manufacturing plant, by the same investors involved in the George Olah plant in Iceland, where CO_2 from residual blast furnace gases will be turned into liquid fuel [54].

The technology status is based on the running and planned projects which are on the demonstration to commercialization stage. More and more concepts and planned demonstrations are emerging for the production of liquid fuels by the power-to-liquid technology. The fast progress is visible even for the more advanced concepts. For example, the Swiss company Climeworks, has constructed an industrial scale atmospheric CO_2 capture plant that has started its operation at the end of 2016 [55]. Based on the results from the currently running plant, in the future the company is aiming to supply air-captured carbon for power-to-gas and power-to-liquid plants. They have already tested this with the Sunfire company in their project in Dresden [56]. Two other companies are pursuing this idea, being Global Thermostat in the USA and Carbon Engineering in Canada. In Finland, VTT Technical Research Center will demonstrate a portable pilot-plant for liquid fuel production from atmospheric CO_2 and electrolytic hydrogen in one compact system. Germany's Karlsruhe Institute of Technology (KIT) has constructed a new compact plant [57].

The use of hydrogen directly in transport is already present and there are around 500 vehicles in Europe already operating [58]. In addition there is a newly granted program for expanding this with 1,200 additional vehicles and 200 fuelling stations in the next 6 years [59]. Hydrogen fuel cell vehicles are in principle electric vehicles where there is on-board electricity production from hydrogen instead of direct electric charging. In response to the regulation from 2014 [60] about deployment of alternative fuel infrastructure including hydrogen, countries are beginning to invest in this technology. Germany plans to be the first country with a basic hydrogen-refuelling network. In December 2017, Germany is planning to launch its first hydrogen powered passenger train [61]. Denmark has 10 hydrogen refuelling stations distributed evenly around the country and 64 hydrogen fuel cell vehicles operating [62]. There is a special parking permit in Copenhagen where the yearly parking ticket for EVs and hydrogen cars are 7 times cheaper than for regular vehicles.

Hydrogen in industry has been used for many years but electrolytic hydrogen is used mostly in cases where it is cost-effective, for example in relation to electricity costs. It is used for the production of fertiliser, ammonia and in the food industry. The largest electrolysis plant has been used for the fertiliser industry [5]. However, it is not expected that hydrogen produced from electrolysis will be competitive for industrial purposes since its use in the transport sector is more valuable.

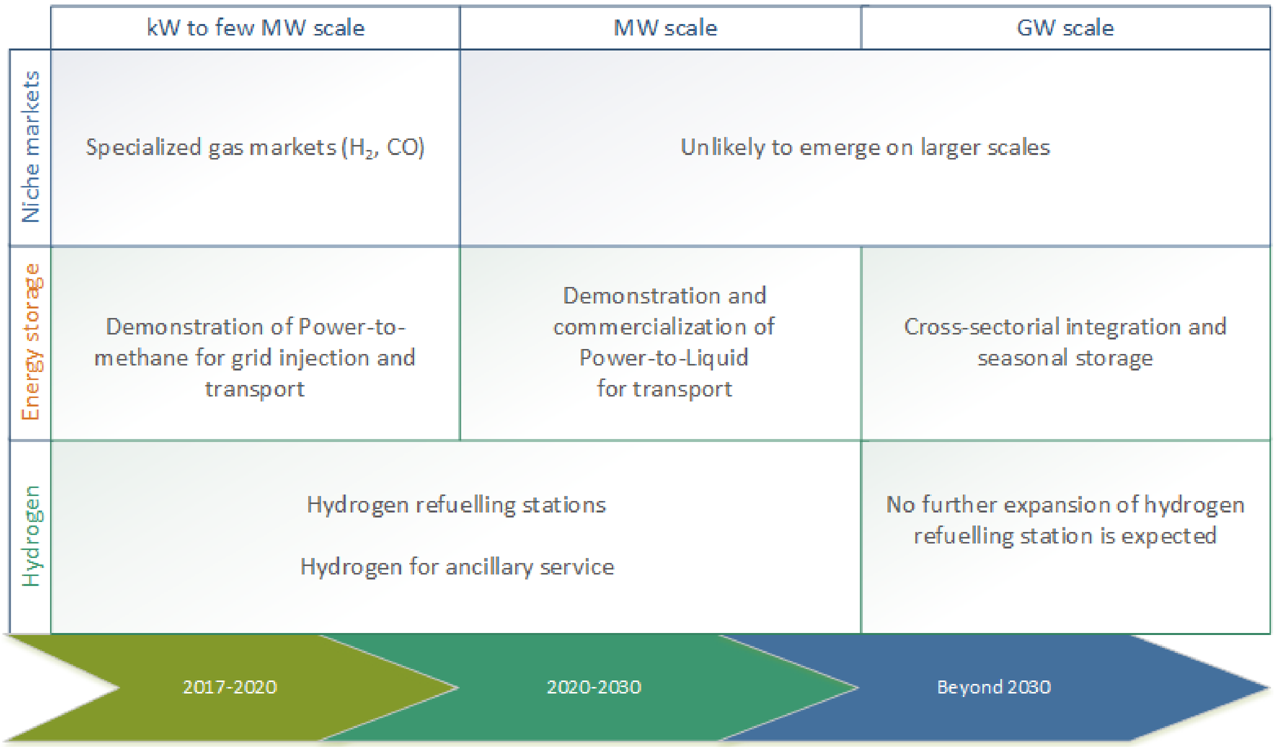
2. Stakeholders’ vision for electrolysis

This section provides an overview of the vision of different stakeholders’ on electrolysis in the present and future energy system. The interviewed stakeholder list is presented in the acknowledgment section of this report and the stakeholders include researchers and company representatives that have been invested or have been part of demonstration projects. The vision is illustrated in Figure 6.

There is a general agreement among the stakeholders that electrolysis will most certainly play a role in the future energy system and that the use of electrolysis can provide the important link between the electricity and transport sector. The limited presence of electrolysis on the market is due to the limited need for this technology in the current energy system. Therefore, in the short term the introduction of electrolysis will emerge in specialized gas markets and industry. To a certain extent since there is no need for the technology now, it carries the stigma of a future technology and with no clear political guidelines on the use of this technology, it is emerging very slowly on the market. The rate of electrolysis implementation will depend on the development of the electricity price since this is reported to be the largest expense when using electrolysis.

The potential use of electrolysis can be summarized in three areas: 1) niche markets, 2) direct use of hydrogen and 3) energy storage. The use of electrolysis for niche markets has already started and its industrial use is slowly emerging. For example, there is a niche market for specialized gases, for example by using SOECs it is possible to do CO_2 electrolysis and provide pure CO for industrial purposes. However, it is not expected that this market will grow significantly in scale in the future. The use of hydrogen for providing ancillary services is becoming more attractive and the first demonstration on a large scale in Denmark will begin operation in 2017. It is not foreseen that the investments in electrolysis will be for this purpose only, but rather that providing ancillary services will be an additional benefit from using electrolysis for fuel production or when upgrading biogas, depending on the operation time and mode. Ancillary services can provide added revenue streams but the investments in the technology should not be driven with the aim of participating in the balancing reserve markets where the expected capacity size can participate due to the poor business case [63].

In the short term until 2020, using hydrogen for transportation purposes and establishing hydrogen refuelling infrastructure is seen as first steps for increasing the share of electrolysis on the market. Even though the production of the renewable hydrogen is not a part of the regulation on deployment of hydrogen infrastructure, it is still expected that a certain share of the hydrogen will come from the electrolysis located at the refuelling stations. The long-term focus for the implementation of electrolysis is for energy storage purposes connected with the production of liquid and gaseous fuels. This is due to the lack of biomass available for energy purposes and the need for new fuel production concepts that can convert electricity from renewable energy to storable chemical energy. Power-to-gas and power-to-liquid technologies with integrated electrolysis are viewed as important after 2020. With more demonstration projects in upcoming years the commercialization of the technology is expected to arrive in the mid 2020s. In the long run, the use of electrolysis for cross-sectorial integration and seasonal storage will come as the technology will hopefully be matured after 2030.



	kW to few MW scale	MW scale	GW scale
Niche markets	Specialized gas markets (H_2, CO)	Unlikely to emerge on larger scales	
Energy storage	Demonstration of Power-to-methane for grid injection and transport	Demonstration and commercialization of Power-to-Liquid for transport	Cross-sectorial integration and seasonal storage
Hydrogen	Hydrogen refuelling stations Hydrogen for ancillary service		No further expansion of hydrogen refuelling station is expected

Figure 6. The role of electrolysis based on stakeholder input

The figure illustrates the expected scale of different technologies. It can be seen that the MW and GW scales are related to energy storage purposes and that the other applications will remain on the smaller scales. In regards to the use of the electrolysis in the energy system it is related to its application. It is expected that the centralized systems with electrolysis will be used for liquid fuel production purposes due to the economy of scale, whilst the gas production and other applications can be seen as distributed generation connected with local gas grids.

Stakeholders agree that the implementation of electrolysis is currently hindered by the electricity price. The electricity price structure can be seen in Figure 7 and it is based on the average electricity price and tariffs for 2016. The state tariff makes up for more than half of the total price, but almost all of this can be refunded due to the electricity being used for process consumption. The total price therefore can be reduced by 44%. After the reduction, the PSO accounts for one third of the price. The PSO will be removed by the government before 2025 and it will be done gradually starting from next year [64]. This could make investments in electrolysis much more attractive. According to [45] there could be additional benefits if the plant is connected to its own electricity production. Although this is not necessarily realistic nor needed if the PSO tariff will be removed.

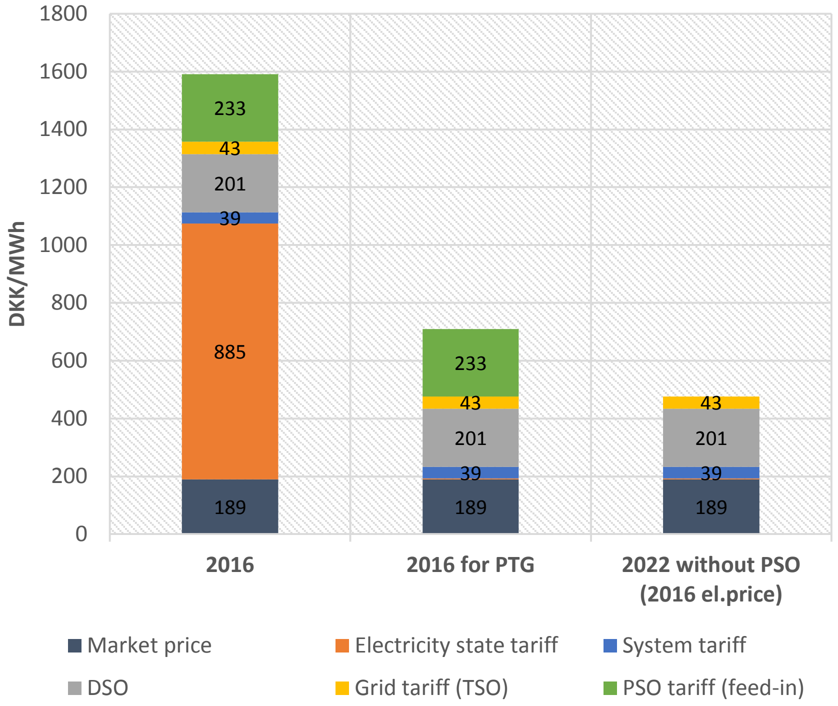


Figure 7. Electricity price structure before, after electricity state tariff refund and without PSO based on 2016 assumptions. Far right represent a future suggested price structure after PSO is removed (market price reflects 2016).

It is agreed upon the stakeholders that more research and demonstration is needed for the SOEC technology, and demonstration of the commercialized alkaline and PEM should be prioritized for desired applications. This is important in order to gain experience and to reduce the technology costs, which are still rather high. There is a need to create a market for electricity storage and for political action that will make a clear path for investments to come. The lack of technology upscaling is due to the investment and operation costs rather than the technical issues that most agree are solvable.

Denmark needs to be better in attracting private investors since the country provides a great testing hub for this technology due to its high shares of wind energy in the electricity production. Denmark can profile itself both as the technology producer and implementer since electrolysis could be a blooming industry in the next decade. The vicious circle of being a technology producer, which can be very expensive due to the high production costs, and not having a local production of technology, which could switch the focus to another technology is important to be taken into consideration.

3. Energy systems and electrolysis projections towards 2020 and 2050

Almost all Danish future energy system projections have recognized electrolysis as an important part of the system to a smaller or larger extent. Therefore, it is important to look into what is necessary to meet these projections and how this relates to the current penetration of electrolysis in the market.

In 2020, the transport sector needs to depend on 10% of its energy needs from renewable sources. With only a few years remaining to meet this goal and Denmark not being the front-runner with these types of initiatives, it is important to look into which scenarios can be followed to meet these goals and which ones are better options for the long-term planning. Electrolysis can be used for transport fuel production as reported previously so this option was compared with other alternatives that could be used for meeting the short-term transport goals. Results from a previous project report [63], shown in Figure 8, illustrate the energy consumption to meet the 10% renewable energy goal. These include the factor counting according to regulation [65] for different fuel types. Biomass based fuels, 2G bioethanol, biogas and electrofuels are adjusted with a factor of two and for EVs whose demand is met with renewable electricity is adjusted with a factor of five. It is visible from the picture that meeting 10% of the liquid fuel demand with 2G bioethanol (if no double counting is accounted) results in using 20% of the Danish biomass potential [66] and almost 13% of the potential if 1G bioethanol is used. This is a very critical outcome if we look into it from the long-term planning since the decisions made today could cause lock-in into certain technology that simply cannot meet the needed demand in the future and can jeopardize biomass overuse. Electric vehicles are a more efficient way to substitute petrol than ethanol fuels in the case of personal transportation. The biomass potential is limited and needs to be prioritized for where it is needed the most in the system. We can see that fuels produced by means of electrolysis can reduce biomass consumption to less than 10% in the case of no double counting according to the regulation in place. Electrolysis can progress further in the future and fully eliminate the need for biomass for fuel production by using CO_2 sources directly from carbon recycling processes [63].

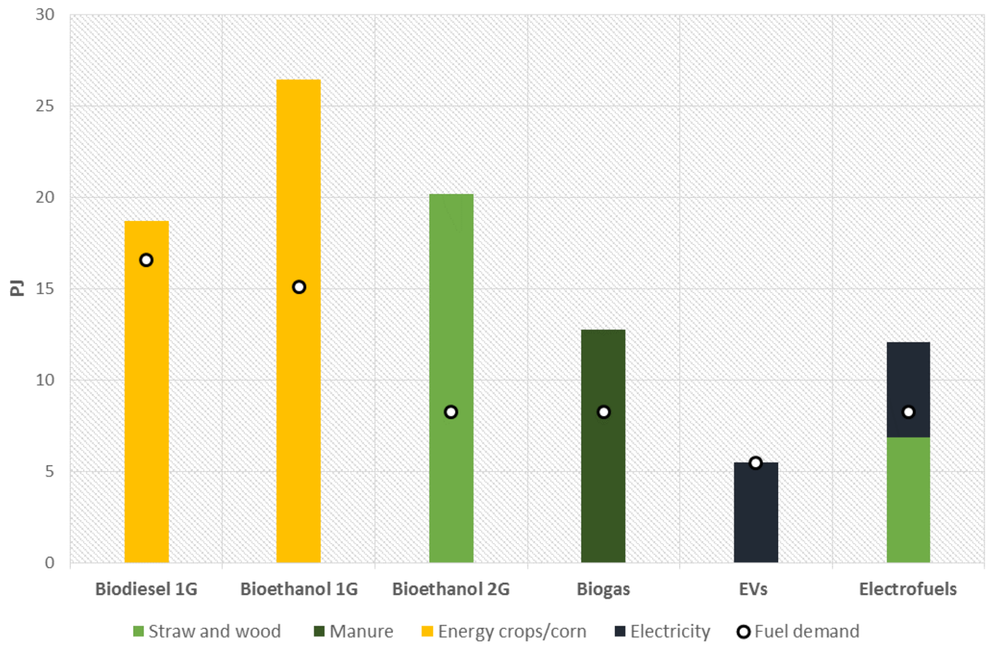


Figure 8. Energy used for meeting the 10% of renewable energy in transport with different fuel types divided in resources needed [63]

The costs related to different fuel production options are illustrated in Figure 9. The costs represent marginal costs in comparison to having no renewable energy in the transport sector. If we take cost assumptions from 2015 it is visible from the figure that the most expensive option are electric vehicles. But with the cost assumptions for 2020, EVs become the third cheapest option after the 1G biodiesel and bioethanol. With biomass issues in mind, we can conclude that electric vehicles are the best option even though Danish projections are very conservative and could even be interpreted as being sceptical. To meet the 10% goal for renewable energy in 2020 with only EVs, almost 400,000 vehicles are needed. The Danish Energy Agency has projected that 6,000 vehicles will be driving in DK in 2020 [67]. However, due to the change in regulation for EVs, implemented from 2016, at the end of 2015 a large number of purchases increased the amount of EVs from 4,523 in June to 7,842 in December [68] and with significantly lower sales in 2016 currently there are 8,013 vehicles registered in Denmark. Denmark does not have any goals for increasing its share of EVs, for comparison, Norway had a goal to reach 50,000 vehicles in 2018, but already this year there are around 100,000 EVs on the road of which 17% are manufactured by Tesla. Instead, the Danish politicians are orienting more towards biomass intensive bioethanol [69].

It is also visible from the figure that electrofuels are in the same cost category as bioethanol, but the biomass used for these fuels is significantly lower. Therefore, these fuels should be the preferred option. Biogas is also an attractive option but it is not suitable for meeting large demands due to the low biogas potential [3]. The decisions made in the next five to ten years are crucial, since they can either open the door for technologies that will be needed in the future or cause a significant delay in the implementation of these technologies.

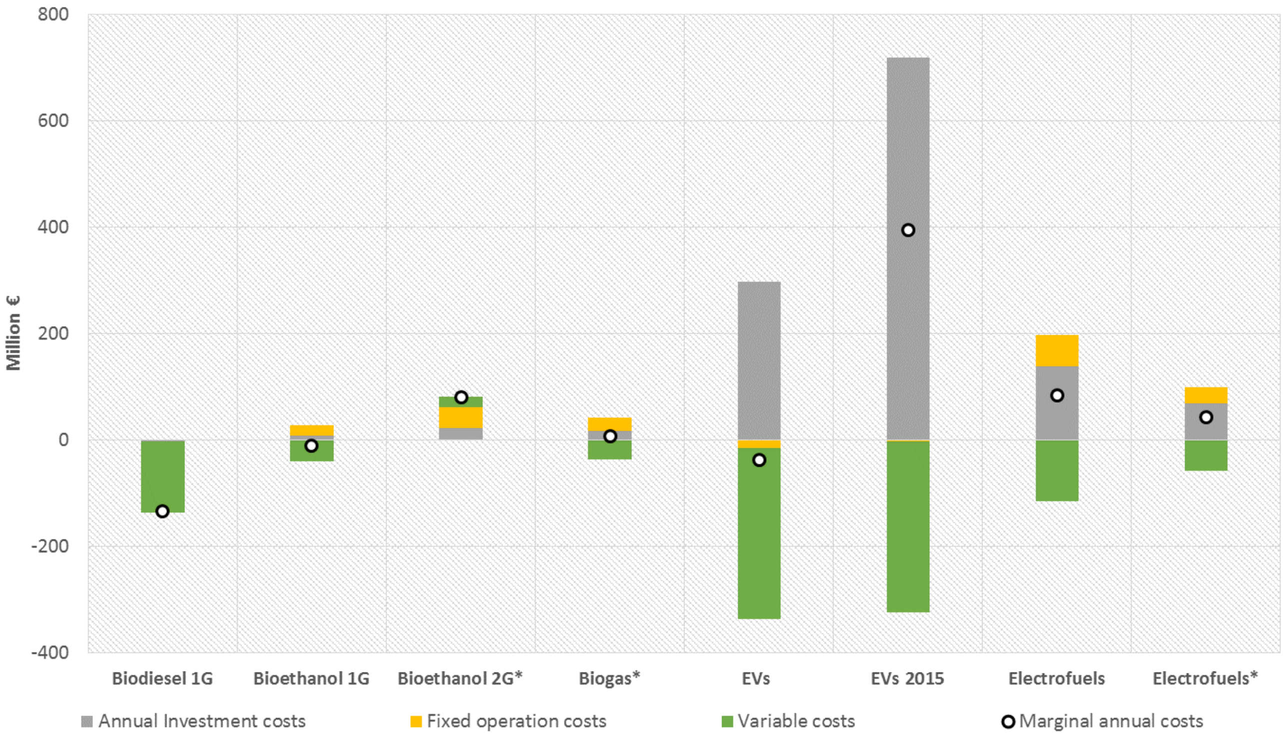


Figure 9. Marginal costs for different fuel options for 2020 in relation to no renewable fuels in the system (*double count for fuels from straw or manure according to directive and factor five for EVs)

Contrary to poor governmental initiatives for the implementation of electrolysis, the energy system projections predict the use of electrolysis in the future Danish energy system for 2050. Two IDA projections (*IDA Energy Vision* further referred to as “IDA” and *IDA Energy Vision+eRoads* further referred to as “IDA+eRoads”) and two DEA projections (Wind and Hydrogen) were compared in order to determine the speed of electrolysis penetration to achieve the projected path of this technology [3,70]. All projections include electrolysis in the transport sector, since this seems to be the most suitable and most suitable sector for this technology. This is aligned with the stakeholders opinion about where electrolysis should be used in the long run. Since there is currently no installed capacity for electrolysis for transport purposes, the starting year of 2016 is marked with 0 MW installed capacity. The projections vary in terms of electrolysis capacity needed for meeting the transport fuel demand, and in terms of which technologies the electrolysis is coupled with for desired fuel production. Consequently, the variation in biomass demand for different projections can be seen (Figure 10).

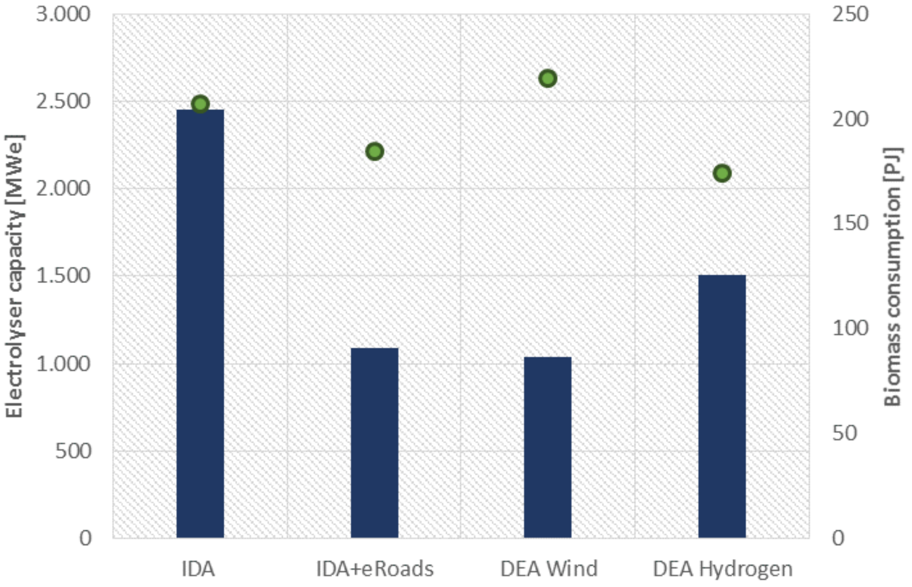


Figure 10. Electrolyser capacity (blue columns) and biomass consumption (green dots) for different 2050 projections

The *IDA* projection has the highest capacity of installed electrolysis, therefore the *IDA+eRoads* scenario was created. In *IDA+eRoads* projection, it is assumed that 20% of the liquid fuel demand can be replaced by the eRoad concept. The eRoad[2] concept is becoming more and more attractive since it offers additional options for direct electrification of the transport sector. The price of batteries in electric vehicles represents the highest share of the vehicle cost, therefore removing the need for the batteries by direct electrification could significantly reduce the investment costs [71]. By implementing the eRoads in the original *IDA* projection, this resulted in a significant reduction in the needed electrolysis capacity. Due to the current status of the technology both *IDA* and *IDA+eRoads* projections utilise alkaline electrolysis in 2020 and SOECs in 2035, whilst both the DEA projections are calculated with utilisation of alkaline electrolysis.

In order to meet the projections, there is a need for significant uptake of electrolysis in the energy system. Figure 11 shows the transition curve for electrolysis for four projections from today to 2035 and Figure 12 shows the transition from 2035 to 2050. In order to create the curves, three-system dimensions for transition were used based on [72]. We can see that depending on the projected capacity of electrolysis in 2035 some curves are steeper than others. The uptake of electrolysis needs to accelerate in the beginning of 2020s if any of the projections are to be realised. We can see that after the acceleration period from the 2020s and 2030s the stabilisation period arrives in the 2040s. It will be necessary to reduce the costs of the technology in order to achieve this large scale implementation.

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[2] eRoads represent direct electrification of vehicles on the go, similar to the existing trains and trolley busses [71].

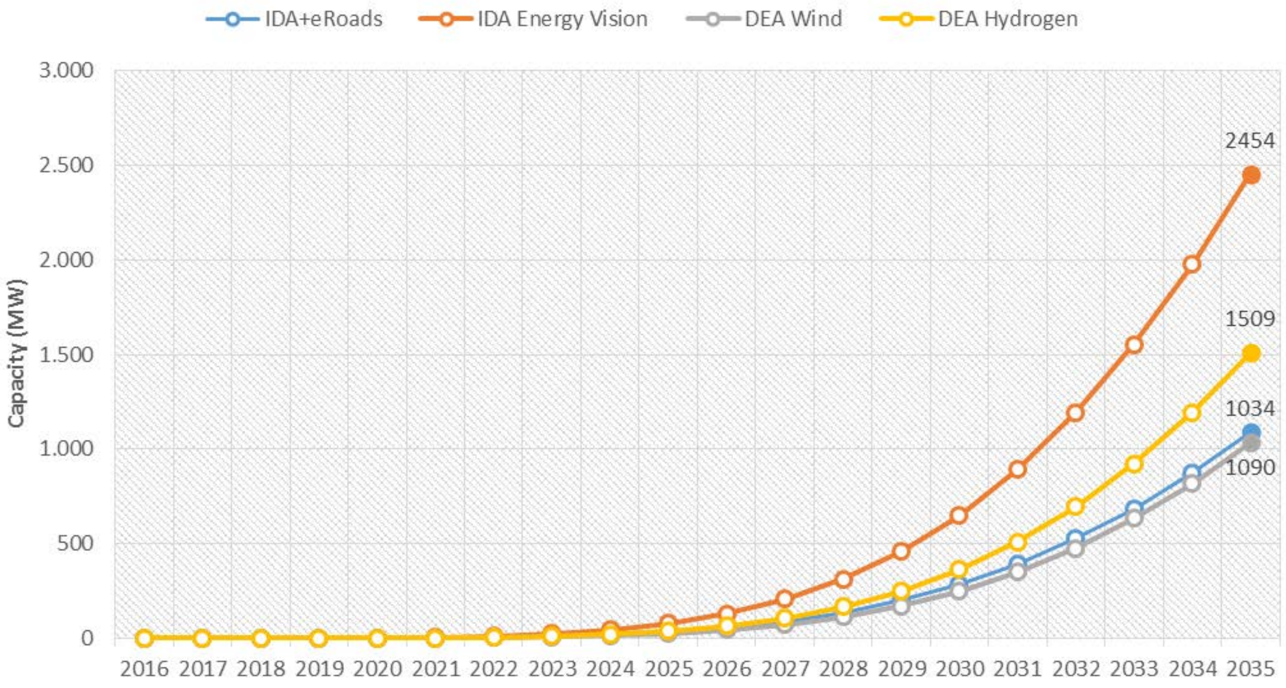

Figure 11. Installed capacity of electrolysis from 2016 to 2035, including the final values for 2035

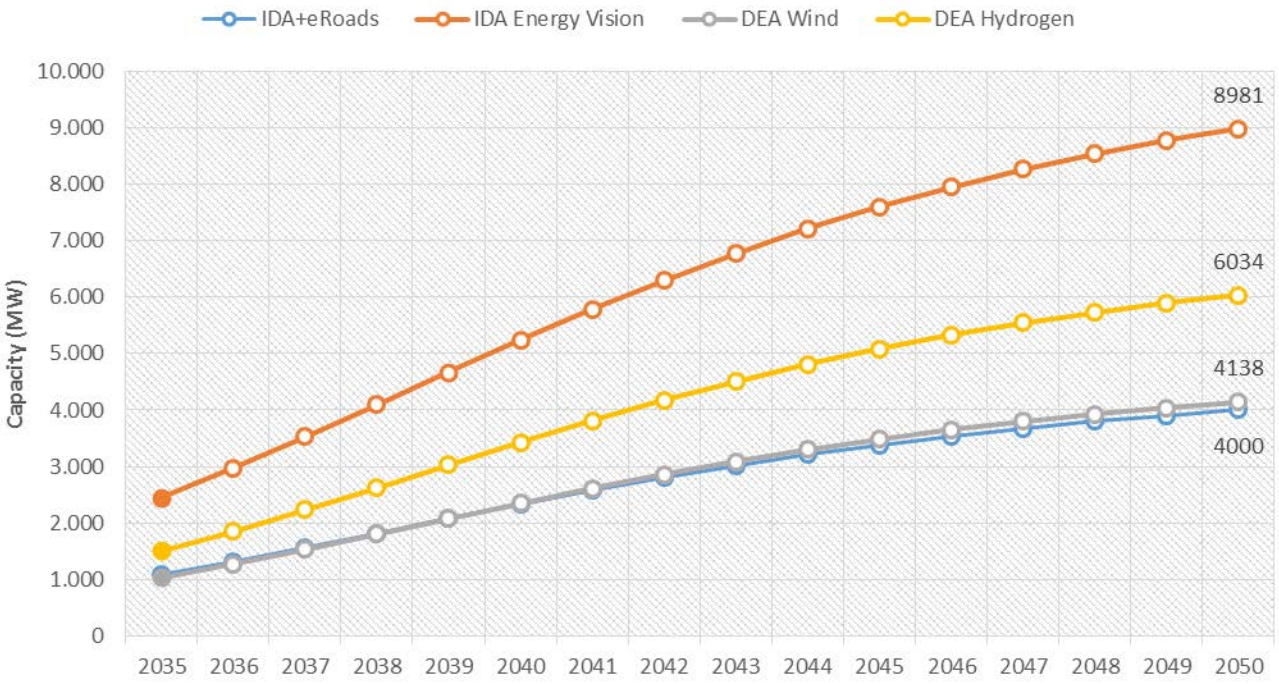

Figure 12. Installed capacity of electrolysis from 2035 to 2050, including the final values for 2050

In order to achieve these capacities there is a need for policy support that will encourage investments. Figure 13 shows the investments in electrolysis per year based on the projection scenarios. The alkaline electrolyser prices from [73] were used for the DEA scenarios and for the IDA scenarios up until 2035 the alkaline electrolyser prices are used and from 2035 onwards the SOEC prices are used [74]. It is visible from the figure that most of the investments are made until 2040 and after that there is a decline in investment due to the reduced installation of new capacity.

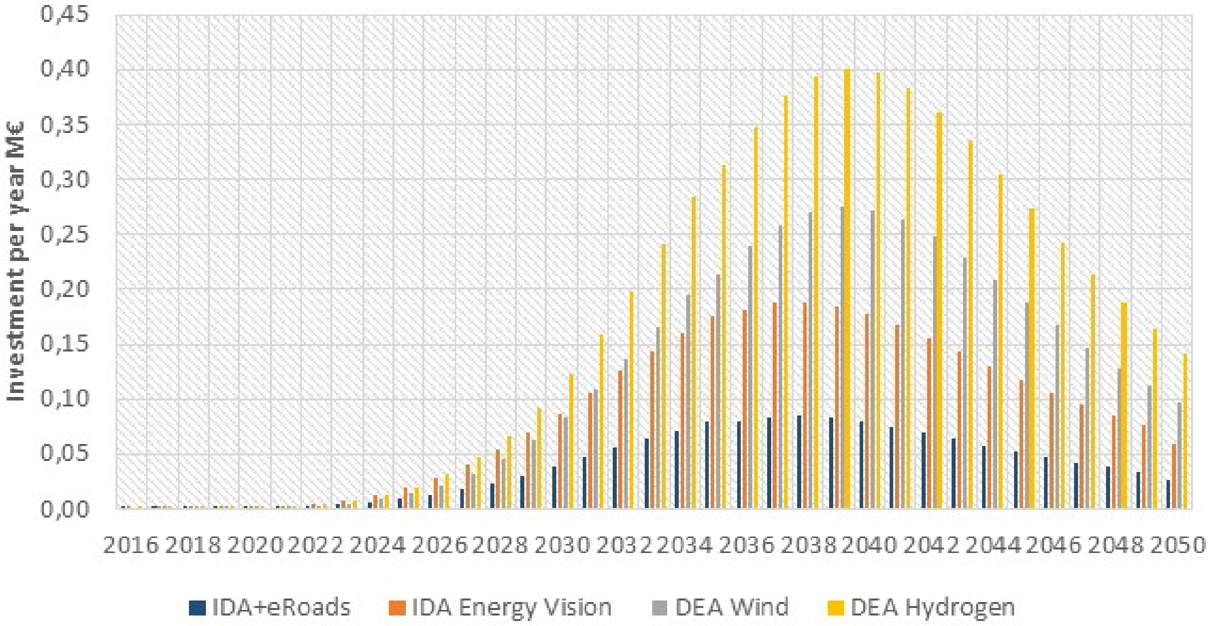

Figure 13. Investments in electrolysis per year for different scenarios

Perspectives

The energy storage of electricity will be required in the future energy systems based on the high share of intermittent renewable energy. Electricity storage in general is much more expensive option than heat and chemical storage, therefore linking the electrons from renewably produced electricity with liquid or gas storage will be a huge advantage in terms of costs and enable the much-needed flexibility in the system. Electrolysers can provide this missing link and can be used in different ways to provide not only flexibility but also sustainable alternatives for transport sector. The power-to-gas and power-to-liquid concepts based on electrolysis are much less water and land intensive, and in case of the biomass or biogas based ones also less biomass intensive, than other options available. The misconception that the readiness levels of these technologies is much lower than the other alternative options and much lower than they truly are, creates a difficult environment to push these concepts on the bigger scale. These technologies are on the similar technological level as any of the more advanced alternative options and have higher environmental benefits than latter.

Stakeholders and the future energy projection studies see electrolysis as an important part of our energy system. However, the technology is not foreseen needed in the current system as the system can provide enough flexibility for the present renewable energy levels. Nevertheless, this picture will change as we continue increasing renewable electricity shares leading to restructuring of the system in which lack of flexibility is compensated with storage and conversion technologies, so called smart energy system. Here power-to-liquid and power-to-gas concepts will play a big role as they present both solution for transport but also a needed flexibility and balancing options. There is a big potential in these technologies, especially the ones based on the CO_2 emissions and production of aviation fuels. With no clear political guidelines, the technology is very slowly emerging on the market making it almost impossible to meet the energy system modelling projections.

The roadmap divided into 4 phases gives a set of activities that are needed to reach electrolysis capacities for transport fuel production in the future, creation of market for this technology as well as restructuring the electricity market that will be needed to support the transition. The aim is to profile Denmark as an important actor in the electrolysis and electrofuel production as country is a great test centre for renewable energy integration and balancing technologies due to already high share of renewables. The demonstration units that explore the synergies of the processes and the operation of combined concept plants for fuel production need to be prioritized. The uncertainty of the natural gas grid role in the future and development of new infrastructure needed in the energy system needs to be further explored.

It is however important not to forget that the fuel synthesis facilities that are part of the P2L concept prefer economy of scale and that there is a concern of being able to provide the resources, either in terms of manure, biomass and CO_2 sources, as well as electricity for electrolysis, in order to meet the fuel demand. Furthermore, it is important not to create another lock-in in our system, where due to the need for CO_2 or electricity we continue providing electricity from fossil power plants and capture CO_2 from them as this is not contributing to either renewable goals nor desired sustainability levels we are aiming at.

References

[1] Stojić DL, Marčeta MP, Sovilj SP, Miljanić ŠS. Hydrogen generation from water electrolysis—possibilities of energy saving. J Power Sources 2003;118:315–9. doi:10.1016/S0378-7753(03)00077-6.

[2] Bhandari R, Trudewind CA, Zapp P. Life cycle assessment of hydrogen production via electrolysis – a review. J Clean Prod 2014;85:151–63. doi:10.1016/j.jclepro.2013.07.048.

[3] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's Energy Vision 2050. Aalborg University; 2015.

[4] Danish Energy Agency. Energiscenarier frem mod 2020, 2035 og 2050 (Energy Scenarios towards 2020, 2035 and 2050). Copenhagen, Denmark: Danish Energy Agency; 2014.

[5] Bertuccioli L, Chan A, Hart D, Lehner F, Madden B, Standen E. Development of Water Electrolysis in the European Union. Fuel Cells and Hydrogen Joint Undertaking; 2014.

[6] Dornburg V, van Vuuren D, van de Ven G, Langeveld H, Meeusen M, Banse M, et al. Bioenergy revisited: key factors in global potentials of bioenergy. Energy Environ Sci 2010;3:258–67.

[7] Gahleitner G. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. Int J Hydrogen Energy 2013;38:2039–61. doi:http://dx.doi.org/10.1016/j.ijhydene.2012.12.010.

[8] Carbon Recycling international. George Olah Renewable Methanol Plant 2012. http://www.carbonrecycling.is/index.php?option=com_content&view=article&id=14&Itemid=8&lang=en.

[9] Beckman K. World's first power-to-liquids production plant opened in Dresden 2014. http://www.energypost.eu/worlds-first-power-liquids-production-plant-opened-dresden/.

[10] Carbon Recycling International. Carbon Recycling International Partners with EU Firms for Power to Fuel Development 2015. http://www.carbonrecycling.is/index.php?option=com_content&view=article&id=67%253Acri-partners-with-eu-firms-for-power-to-fuel-development-&catid=2&Itemid=6&lang=en (accessed February 9, 2015).

[11] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy Storage and Smart Energy Systems. Int J Sustain Energy Plan Manag 2016;11:3–14. doi:10.5278.

[12] Energinet.dk. Electricity generation in 2015 n.d. http://www.energinet.dk/EN/KLIMA-OG-MILJOE/Miljoerapportering/Elproduktion-i-Danmark/Sider/Elproduktion-i-Danmark.aspx (accessed January 3, 2017).

[13] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

[14] Lund H. Renewable energy systems - A smart energy systems approach to the choice and modelling of 100% renewable solutions. Second edi. ELSEVIER; 2014.

[15] Reinaud J, Clinckx N, Ronzeau K, Faraggi P. Scaling up innovation in the Energy Union to meet new climate, competitiveness and societal goals - Scoping the future in light of the past. 2016.

[16] Energiforskning.dk. El-opgraderet biogas | Energiteknologiske forskningsprojekter 2013. http://energiforskning.dk/en/node/7155 (accessed March 10, 2015).

[17] Energinet.dk. Biogas i tal n.d. http://www.energinet.dk/DA/GAS/biogas/Om-biogas/Sider/Biogas-i-tal.aspx (accessed January 14, 2017).

[18] KIC InnoEnergy. Energy from Chemical Fuels. Strategy and Roadmap 2015-2019. Eindhoven: 2015.

[19] BioCat Project. Power-to-gas via Biological Catalysis (P2G-BioCat) 2014. http://biocat-project.com/ (accessed October 29, 2015).

[20] Wittrup S. Dong lukker sit højt profilerede forgasningsanlæg til 150 millioner kr. n.d.

[21] Energi G. Gothenburg Biomass Gasification Project, GoBiGas n.d.;http://www.

[22] Knudsen JN, Jensen JN, Vilhelmsen P-J, Biede O. Experience with CO_2 capture from coal flue gas in pilot-scale: Testing of different amine solvents. Energy Procedia 2009;1:783–90. doi:10.1016/j.egypro.2009.01.104.

[23] Around the world in 22 carbon capture projects | Carbon Brief n.d. https://www.carbonbrief.org/around-the-world-in-22-carbon-capture-projects (accessed March 3, 2017).

[24] Lomax G, Lenton TM, Adeosun A, Workman M. Investing in negative emissions. Nat Clim Chang 2015;5:498–500.

[25] Schmidt P, Weindorf W, Roth A, Batteiger V, Riegel F. Power-to-liquids. Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. Munich: 2016.

[26] Pérez-Fortes M, Schöneberger JC, Boulamanti A, Tzimas E. Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment. Appl Energy 2016;161:718–32. doi:10.1016/j.apenergy.2015.07.067.

[27] Ridjan I, Mathiesen BV, Connolly D, Hansen K, Wunsch JH. Applications of SOECs in different types of energy systems - German and Danish case studies. Copenhagen, Danmark: Department of Development and Planning; 2015.

[28] Commission E. Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and ame. Brussels: Official Journal of the European Union; 2009.

[29] Methanol Institute. Methanol Gasoline Blends - Alternative Fuel For Today's Automobiles and Cleaner Burning Octane For Today's Oil Refinery. 2016.

[30] European Commission. Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the promotion of the use of energy from renewable sources (recast) - COM(2016) 767 final. Brussels, Belgium: European Commision; 2016.

[31] Corporation VT. VOLVO BIO-DME. Unique field test in commercial operations, 2010–2012. 2012.

[32] CRI - Carbon Recycling International. Carbon Recycling International launches fleet test of Geely Emgrand 7 methanol powered vehicles n.d. http://carbonrecycling.is/news/2016/4/13/carbon-recycling-international-launches-fleet-test-of-geely-emgrand-7-methanol-powered-vehicles (accessed February 6, 2017).

[33] Poland at Sea. Stena Line methanol project shortlisted for Global Freight Awards n.d. http://www.polandatsea.com/stena-line-methanol-project-shortlisted-for-global-freight-awards/ (accessed February 6, 2017).

[34] Hellsmark H, Jacobsson S. Realising the potential of gasified biomass in the European Union - Policy challenges in moving from demonstration plants to a larger scale diffusion. Energy Policy 2012;41:507.

[35] The Poul la Cour Museum. Storing wind power n.d. http://www.poullacour.dk/engelsk/vindkraften.htm (accessed December 9, 2016).

[36] Zeng K, Zhang D. Recent progress in alkaline water electrolysis for hydrogen production and applications. Prog Energy Combust Sci 2010;36:307–26. doi:10.1016/j.pecs.2009.11.002.

[37] Hydrogen NEL. Product leaflet – NEL P60 Pressurized electrolyser n.d.;2013.

[38] Smolinka T, Gunther M, Garche J. now-studie: stand und entwicklungspotenzial der wasserelektrolyse zur herstellung von wasserstoff aus regenerativen energien. technical report - Google-søgning 2011;2013.

[39] Paidar M, Fateev V, Bouzek K. Membrane electrolysis—History, current status and perspective. Electrochim Acta 2016;209:737–56. doi:10.1016/j.electacta.2016.05.209.

[40] Carmo M, Fritz DL, Mergel J, Stolten D. A comprehensive review on PEM water electrolysis. Int J Hydrogen Energy 2013;38:4901–34. doi:10.1016/j.ijhydene.2013.01.151.

[41] Ursua A, Gandia LM, Sanchis P. Hydrogen Production From Water Electrolysis: Current Status and Future Trends. Proc IEEE 2012;100:410–26. doi:10.1109/JPROC.2011.2156750.

[42] Smart Grids and Energy Storage: World's Largest Hydrogen Electrolysis Facility n.d. http://www.siemens.com/innovation/en/home/pictures-of-the-future/energy-and-efficiency/smart-grids-and-energy-storage-largest-hydrogen-electrolysis-facility.html (accessed January 3, 2017).

[43] Siemens, Blue Fuel Energy. Siemens and Blue Fuel Energy to install 20 MW of SILYZER-200 PEM technology 2014.

[44] HyBalance project 2016. http://hybalance.eu/ (accessed July 20, 2016).

[45] Jensen JK, Grahl-Madsen L, Jørgensen J, Yde L, Hendriksen PV, Jensen TL. Strategi for elektrolyse. 2016.

[46] Marini S, Salvi P, Nelli P, Pesenti R, Villa M, Berrettoni M, et al. Advanced alkaline water electrolysis. Electrochem Front Glob Environ ENERGY 2012;82:384–91. doi:http://dx.doi.org/10.1016/j.electacta.2012.05.011.

[47] Brisse A, Schefold J, Zahid M. High temperature water electrolysis in solid oxide cells. Int J Hydrogen Energy 2008;33:5375–82. doi:10.1016/j.ijhydene.2008.07.120.

[48] SOPHIA | solar integrated electrolysis n.d. http://www.sophia-project.eu/ (accessed December 10, 2017).

[49] Eco - Efficient Co-Electrolyser for Efficient Renewable Energy Storage n.d. http://www.eco-soec-project.eu/ (accessed December 10, 2017).

[50] Seier J. Demonstration Projects on Energy Storage Technologies in Germany 2016.

[51] de Bucy J, Lacroix O, Jammes L. The potential of Power-to-Gas - Technology review and economic potential assessment. Paris: 2016.

[52] Electrochaea's First Methane Production n.d. http://www.electrochaea.com/latest-news/electrochaeas-first-methane-production/ (accessed December 10, 2017).

[53] Bailera M, Lisbona P, Romeo LM, Espatolero S. Power to Gas projects review: Lab, pilot and demo plants for storing renewable energy and CO2. Renew Sustain Energy Rev 2017;69:292–312. doi:10.1016/j.rser.2016.11.130.

[54] CRI - Carbon Recycling International. CRI's power-to-methanol technology at steel manufacturing plant in Sweden n.d. http://carbonrecycling.is/news/2016/11/17/cris-power-to-methanol-technology-at-steel-manufacturing-plant-in-sweden (accessed January 3, 2017).

[55] Climeworks. About the pilot and demonstration project n.d. http://www.climeworks.com/about-project.html (accessed January 3, 2017).

[56] ScienceAlert. Scientists are building a system that could turn atmospheric CO2 into fuel n.d. http://www.sciencealert.com/scientists-are-building-a-system-that-could-turn-atmospheric-co2-into-fuel (accessed January 4, 2017).

[57] Mack E. Reactor that produces liquid fuel from CO2 in the air to be tested in portable pilot plant 2016. http://newatlas.com/carbon-dioxide-fuel-pilot-plant-finland-kit-ineratec/46362/ (accessed December 13, 2016).

[58] Hydrogen Europe. The ultimate guide to fuel cells and hydrogen technology. Brussels: 2015.

[59] ITM Power. €35m H2ME2 European Hydrogen Refuelling Station deployment 2016. http://www.itm-power.com/news-item/e35m-h2me2-european-hydrogen-refuelling-station-deployment) (accessed January 4, 2017).

[60] European Parliament. Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure. Brussels, Belgium: 2014.

[61] O'Sullivan F. Germany Has the World's First Hydrogen-Powered Train 2016. http://www.citylab.com/commute/2016/09/germany-hydrogen-passenger-train/501575/ (accessed January 4, 2017).

[62] Brintbiler.dk n.d. http://brintbiler.dk/ (accessed December 6, 2017).

[63] Ridjan I, Hansen K, Sorknæs P, Xu J, Connolly D, Mathiesen BV. The role of electrolysers in energy systems - Energy markets, grid stabilisation and transport fuels. Department of Development and Planning; 2016.

[64] Lov om ændring af lov om elforsyning, lov om fremme af vedvarende energi og elsikkerhedsloven og om ophævelse af lov om tilskud til fremme af vedvarende energi i virksomheders produktionsprocesser (Udfasning af PSO-opkrævning, ophævelse af ForskEL, finans. Energi-, Forsynings- og Klimaministeriet; 2016.

[65] European Commission. DIRECTIVE (EU) 2015/1513 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewabl. Official Journal of the European Union; 2015.

[66] Wenzel H, Høibye L, Hamelin L, Rune Duban G, Neil Bird D, Strange Olesen A, et al. Carbon footprint of bioenergy pathways for the future Danish energy system. Denmark: COWI; 2014.

[67] Energisyrelsen. Analyse af alternative muligheder til opfyldelse af 2020 målet for VE til transport. 2015.

[68] Dansk Elbil Alliance. Bestand af elbiler i Danmark n.d. http://www.danskelbilalliance.dk/Statistik/Bestand_modeller.aspx (accessed October 18, 2016).

[69] Duus SD. Biobrændstof stemt igennem på Christiansborg n.d. http://energiwatch.dk.zorac.aub.aau.dk/secure/Energinyt/Olie___Gas/article9229667.ece (accessed December 18, 2016).

[70] Danish Energy Agency. Danmarks energi- og klimafremskrivning 2014 (Denmark's energy and climate projection 2014). Danish Energy Agency; 2014.

[71] Connolly D. eRoads: A comparison between oil, battery electric vehicles, and electric roads for Danish road transport in terms of energy, emissions, and costs. 2016.

[72] Rotmans J, Kemp R, Asselt, M V. More evolution than revolution: transition management in public policy. J Futur Stud Strateg Think Policy 2001;3.

[73] Danish Energy Agency, Energinet.dk. Technology data for energy plants. Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion. vol. 2013. Danish Energy Agency and Energinet.dk; 2012. doi:ISBN: 978-87-7844-931-3.

[74] Ridjan I. Integrated electrofuels and renewable energy systems. Department of Development and Planning, 2015.