The Role of Power-to-X in a Sustainable Energy System Based 100% on Renewables

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Abstract. To stop global warming, all sectors must become climate neutral. To reach this aim energy use must be reduced, efficiency must be increased and the remaining energy demand must be covered by renewables. This 100 per cent renewables supply will lead to a regular and cyclic energy over supply. However also sectors which can not be electrified directly must be connected to electricity sector. Power to Liquid (PtL) is one possible sector coupling technology. PtL production can be operated in times with renewable energy excess. In times of less renewable production a reduction of the actual production of a PtL plant, this can help to stabilise the power supply in the public grid and the market values of renewable energies.

This enables the substitution of fossil by synthetic carbon neutral fuels, first of all in aviation and maritime transport. Today it is allowed to substitute 50 per cent of the fossil kerosene in aviation by synthetic kerosene. To reach this drop-in quota and increase it in future further a consistent and accelerated expansion of renewable energies must be realized. Of course, it must be expanded to reach a 100 per cent synthetic fuel quota for the remaining hydrocarbons which have to be used in aviation, maritime transport and other sectors. Note, synthetic fuels are only carbon neutral if the CO_2, which is needed for the production, is kept in a closed CO_2 cycle. In addition, synthetic kerosene is burned in the engines of a plane. This will lead to non CO_2 effects, which will lead to global warming, too. Therefore, using synthetic kerosene can only lead to carbon neutral aviation, and if further ecological and social aspects are not being negelected, a transformation into a truly sustainable energy system is feasible.

Keywords: PtX · sector coupling · synthetic jet fuel · carbon cycle · green hydrogen

1 Introduction

To slow down global warming, the reduction of greenhouse gas emissions is inevitable. The Paris Agreement calls the international community for limiting global warming to below 2 °C, ideally to 1.5 °C. Electrification with renewable energies makes it possible to transform large parts of the energy system in a greenhouse gas-neutral way. With the help of Power-to-X (PtX) technologies, renewable electricity can be used for aviation and maritime transport, to provide space heating, gaseous and liquid energy sources as well

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as basic chemical materials. In this way, the climate impact can be reduced in areas that are difficult to electrify directly. However, this flexibility comes at the cost of additional energy demand at each conversion step and thus, lowers the overall efficiency. Therefore, PtX products should only be used where direct electrification is not possible. Moreover, only absolutely necessary conversion steps should be carried out, and they only contribute to climate neutrality if the input energy is renewable. But, even though solar and wind power are available in abundance on this planet, the capacities are still limited due to an inefficient allocation of public and private financial resources and the lack of political will in the last decades. In the future, renewable energy resources will be limited by an increasing competition for raw materials. Therefore, it is absolutely necessary that the use of PtX products must be prioritised in areas where direct electrification is not feasible in the next decade at the current state of knowledge and technology.

International Aviation accounts in 2018 for 2.8% of global greenhouse gas (GHG) emissions. This is in addition to 2–5 times the climate impact of non-CO_2 effects. These are water vapor, nitrogen oxide (NOx) emissions, direct and indirect aerosol effects, and contrails cirrus [1]. Individually, they can have a cooling or warming effect, but in total a warming effect can be observed [2]. The greenhouse gas emissions of maritime transport have a global share of 3%. Even though each of them are in the range of an industrial country like Germany or Japan, and that the Paris Agreement requires developed countries to set economy-wide emission reduction targets and developing nations to work towards those, none of the 196 NDCs include a specific target for emissions from international aviation. The EU and its 27 member states include emissions from outgoing flights in its NDC [3]. Most countries rely on the leadership from ICAO and IMO, including the US and the UK, but those are assessed as insufficient by many analysts.

Furthermore, international aviation and shipping are two sectors which cannot be directly electrified in the medium term due to, amongst others, long investment cycles and the required energy density of fuels in air planes and ships. To reduce the GHG emissions from these sectors the fossil fuels can be substituted by synthetic fuels, which must be produced carbon neutral manner. Due to the urgent need to make international aviation carbon neutral, the following focuses on this sector. In general, however, these considerations are transferable to maritime transport.

2 PtL Production Technology

2.1 Production Route

Power-to-liquid (PtL) describes the conversion of renewable electric energy to liquid energies like synthetic fuels such as kerosene, methanol or ammonia. Synthetic kerosene can be produced by the so called Fischer- Tropsch synthesis or by the synthesis of methanol [4]. The first has the advantage that a blending of up to 50% (drop-in) synthetic kerosene with fossil kerosene is already permitted in aviation today. PtL fuels which were produced by renewable electicity are also called Renewable Fuels Non-Biological Origins (RFNBO).

Regardless of the manufacturing process and the final product, the starting material for production is hydrogen (Fig. 1). As with fossil fuels, the final outputs are also hydrocarbons. The carbon demand is covered by carbon dioxide, whereas the Fischer-Tropsch

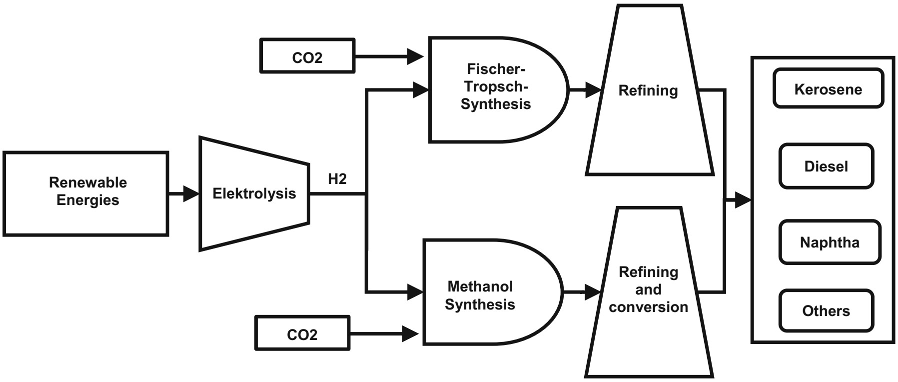


Fig. 1. PtL production process via Fischer-Tropsch and Methanol synthesis. SynGas processing (e.g. reverse water gas shift reaction) for Fischer-Tropsch- Synthesis is not depicted.

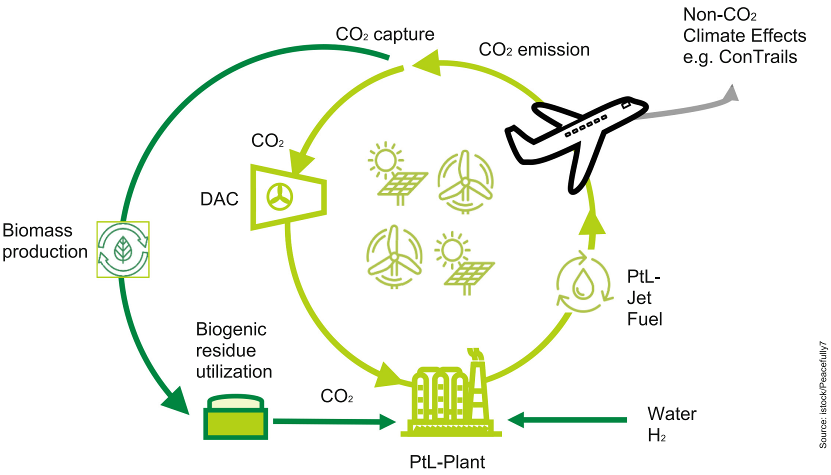
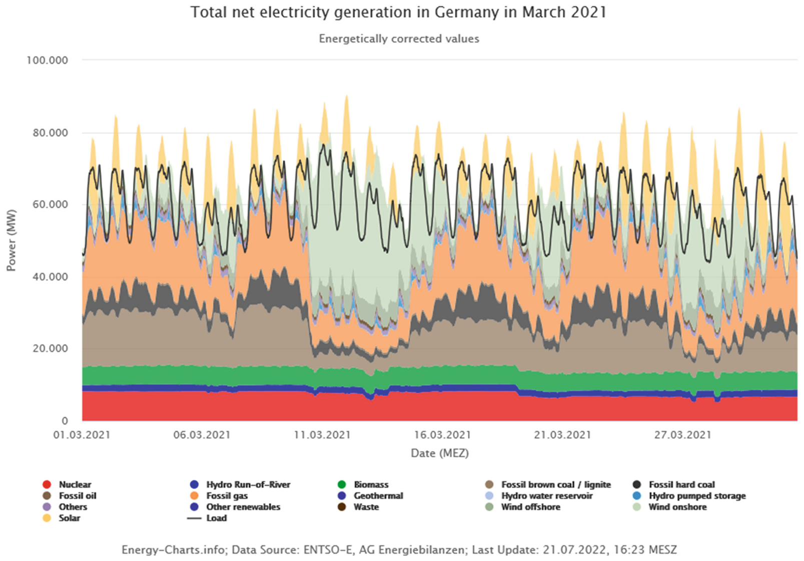


Fig. 2. Closed CO2 cycle for the carbon neutral production of PtL in different time scales (Direct Air Capture and Biomass as carbon source).

synthesis requires the CO_2 to be converted into carbon monoxide (CO). Hydrogen and carbon monoxide form a synthesis gas (SynGas) that acts as a feedstock in the Fischer-Tropsch synthesis. The direct output is a synthetic crude oil (SynCrude). The final products can be processed in normal refineries. The formation of the SynGas in case of Methanol is done in the methanol reactor. If the methanol is not used directly as fuel, it can be processed also into fuels like kerosene, diesel or naphtha. Therefore additional steps for the formation the right length of the hydrocarbon chain are needed.



Energy-Charts.info; Data Source: ENTSO-E, AG Energiebilanzen; Last Update: 21.07.2022, 16:23 MESZ

Fig. 3. Total energy production in Germany in March 2021. The black line indicates the load, yellow is solar power and light green wind power. [www.energy-charts.info]

2.2 Electrolysis

This hydrogen must be produced using electric renewable energy. It is then referred to as green hydrogen. This can be done by electrolysis. There are several technologies available: Alkaline electrolysis (AEL) is a robust and for several years proven technology, but so far multi-mega-watt stacks are not available on the market. In addition, abundant raw materials is needed, which leads to comparable low investment costs. Further disadvantages are low powerdensities followed by a large CO_2-footprint, as well as gas purification is needed to comply with the purity requirement, limited adjustability and low cold start performance.

Proton exchange membrane electrolysis (PEM) shows higher power densities, enables a highly flexible operation high purity of the product gas. On the other hand, rare and expensive materials are needed. Furthermore, the lifetime of PEM is lower compared to AEL [5]. Both technologies are low temperature processes between 60 and 90 °C. Solid oxide electrolysis (SOEL) is a high temperature technology. The advantage is that SynGas can be produced directly by adding CO_2. However, the technology shows the lowest technology readiness level compared to AEL and PEM and is less proven.

Electrolysis accounts for the majority of the energy demand for PtL production. For a carbon neutral production, it is crucial that electrolysis and all other production steps are carried out with renewable energy. The needed renewables capacity must be installed in addition to production capacities which have to cover the energy demand of other users. This criterion is often referred to “additionality” and found its way into the draft delegated act to Article 27 of the Renewable Energy Directive II of the European Commission.

Table 1. CO_2 sources and available concentration [6]

CO_2 source	CO_2 concentration
Combustion process	10–15 vol.-%
Concrete production	14–33 vol.-%
Biogas (Biomethane)	25–45 vol.-% (~ 99 vol.-%)
Ambient air	0.04 vol.-%

2.3 Closed Carbon Cycle

Besides hydrogen, a carbon source is needed for the production of synthetic hydrocarbons such as jet fuel. Between 3.1 and 3.4 tons CO_2 are needed for the production of one ton of synthetic hydrocarbon [6]. The CO_2 should be available for the production process without any impurities. Typically this feedstock demand will be covered by a source which is easy and cheap available. Table 1 shows four commonly discussed CO_2 sources and the CO_2 concentration typically present in exhaust gas streams from industrial processes.

After combustion in an engine or jet turbine, the carbon is released into the atmosphere in the form of CO_2. This clearly shows that, for example, an aircraft powered by PtL will only be carbon neutral if the CO_2 is needed to produce the synthetic jet fuel has first been removed from the atmosphere. Of course, it is not possible to capture the emitted CO_2 directly at the plane. It is important, however, that the same amount of CO_2 is removed from the atmosphere in a short time after emission (Fig. 2). Industrial point sources like combustion processes or concrete production can deliver high amounts of CO_2 on a specific side. But it is quite clear, that these sources are only shifting the CO_2 emissions from one sector to another. However, the number of these sources is to low to cover the fuel demand by PtL [6]. DAC enables the separation of CO_2 in short time distance to the emission due the combustion process in the airplanes engine. Per ton CO_2 an energy demand of approx. 2 MWh occurs [7], thermodynamically lowest energy demand is around 0.5 MWh/ t CO_2. In a modular way, this process can be installed on every site and can cover the CO_2 demand of a big scale PtL plant. In the actual phase of market ramp up not enough DAC capacities are available. For a transitional period, the CO_2 demand can be met by biomass respectively by capturing CO_2 from biogas. The timescale for capturing the CO_2 form the atmosphere is longer compared to DAC, but also much shorter compared to fossil sources. Of course, the feedstock of the biogas plant should be biogenic residues. Typically, the capacity of a biogas plant is comparable small. Following by this, only small PtL plants can be supllied by this CO_2 feedstock. In addition, it should be avoided that the development of PtL production stimulates the construction of new biogas plants, whose raw material competes with food production.

2.4 Efficiency

Hydrogen electrolysis and Fischer-Tropsch synthesis are the main processes with the highest losses. Efficiency rates of between 62 and 85 percent are currently achieved

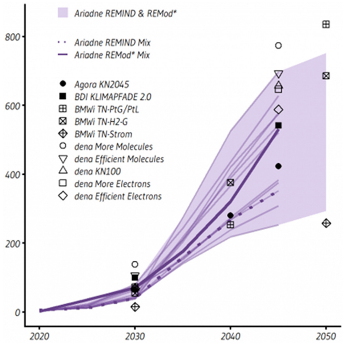


Fig. 4. Bandwidths of the demand for hydrogen and e-fuels in TWh/a in scenario analyses for achieving climate neutrality in Germany [9]

for hydrogen electrolysis, and 56 percent for Fischer-Tropsch synthesis [4]. In addition, there are energy losses due to the SynGas processing and other auxiliary components. Thus, an overall efficiency from hydrogen electrolysis to kerosene via Fischer-Tropsch Synthesis can be achieved by a maximum efficiency of 38 to 48 percent using low temperature electrolysis and 45 to 60 percent using high temperature electrolysis [8]. Note, also losses due to the refinery process and the efficiency of the engine has to be taken into account.

3 Energy Demand

3.1 Energy Demand by PtL Plants

Compared to direct electrification, the use of PtL fuels require 2.5 to 5 times the amount of energy. This underlines the need for increased and accelerated development of renewable energies. In 2018, the jet fuel demand in Germany was 10 million tons, and 47 million tons in the EU. This corresponds to an energy content of 120 TWh in Germany and 564 TWh in the EU. To meet the jet fuel demand with PtL kerosene in Germany, 266 TWh of electrical energy would be required under the optimistic assumption of an overall efficiency of 45 percent, plus the energy required to supply the necessary CO_2. To meet the demand in the EU, 1,253 TWh would be required to meet the jet fuel demand. Note, this is only the energy which is theoretical required for the production of jet fuel through he Fischer-Tropsch synthesis. In this process, however, only a portion is processed into jet fuel. The kerosene yield is between 50 and 70 percent, with the remainder being divided into diesel, naphtha and waxes. Consequently, for the amount of kerosene required, depending on the jet fuel yield, the energy required for the overall process is correspondingly higher.

However, the demand for renewable energies should not be considered in isolation for the production plants, but in the overall system. Figure 3 shows the power production and consumption in Germany in March 2021. The power production of solar (yellow) and wind (light green) power shows the typical fluctuating behaviour. The power consumption is indicated by the black line (load). It is clearly visible that production is regularly higher than consumption at some times. Actually, this overproduction is exported or partly cut off. A higher share of renewable energies in the electricity system will lead regularly to temporary overproduction of power due to the fluctuating nature of renewables, which would be cut off in the absence of demand.

3.2 Ptl and the Power Grid

In theory, this surplus can be effectively used for production of PtX products as type of energy storage. But this needs to examined in more detail. It clear already a power system stabilization function depends on several factors linked to the specific technology and plant set-up, in particular due to varying requirements for the number of full load hours and for constant production, as well as the plant site with its associated transport requirements and costs.

Especially electrolysers and DAC units can be easily adjusted to the fluctuating supply of renewable electricity. They can act as positive and negative balancing power. The reconversion of green hydrogen for covering increased load is discussed as well as the conversion into hydrogen derivates that will be used as energy carrier in other sectors.

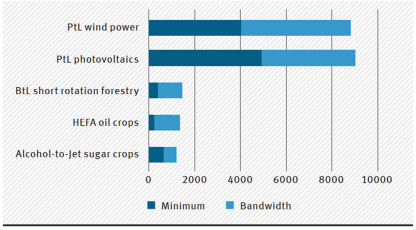
With regards to PtL, the costs of the final product is dominated by the energy price. In times of energy excess, the price of electrical energy decreases. Consequently, the use of this excess energy for operating PtL plants will lead to a decrease of the production costs for synthetic kerosene. However this can provide benefits for the entire energy system.

Next to the technological perspective, PtL plants could possibly serve as grid relief from an economic point of view. Research shows that electrolysers function as a permanent price stabiliser in the market for wind and solar electricity, since the natural decline of the market values towards zero of these is halted by adding this flexible electricity demand in low-price hours [9]. In a power system with high shares of renewables situations may occur when energy production is higher than the demand. In this case, the power output of the generating entity would have to be reduced. If the plant design is smart enough, a PtL plant can use this over production, especially by electrolysis. This could reduce the cost of grid expansion and regulation. However, additional storage may have to be installed within the PtL production to ensure operation.

Therefore, in an energy system based 100% on renewables, the criterion of additionality is overlaid by the requirement of system serviceability. A detailed analysis of the market constellations including the increasing degree of renewable energies in the energy mix, and the retrieved necessary changes in the power purchase criteria for PtL kerosene has been carried out by the ifeu Institute [10].

3.3 Energy Scenarios

In recent years, a number of energy scenarios have been developed for Germany that have dealt intensively with transformation paths towards climate neutrality in 2045 or 2050, namely the main 5 scenarios studies are published by the UBA [13], the Ariadne project [9], Agora [14], dena [15] and by the BDI [16]. All scenarios rely on a mix of measures



Source: LBST/BHL, 2016

Fig. 5. Achievable range per hectare of land for an Airbus A320neo as on example in km/ (ha · year) [7]

to achieve greenhouse gas neutrality. One of these measures is the massive reduction of primary energy demand, which is to be achieved in particular through efficiency gains with the help of electrification of the application sectors, the expansion of renewable energies (RE) and the use of PtX products. Scenarios have incorporated PtX as means to decarbonise hard-to-abate sectors and have forecasted the speed and scope of its market ramp-up. As shown by the Potsdam Institute for Climate Impact Research [9], see Fig. 4, the five recent main German energy scenarios show a wide range of future hydrogen and PtX requirements, resulting in shares of in final energy between 10% and 35%. The scenarios show a high import demand for synthetic energy carriers. This is mainly due to the limited potential of renewable energies and their comparatively low number of full load hours in Germany. This also leads to the prioritisation of direct electrification in the application sectors due to its higher efficiency. The scenarios show a high import demand for synthetic energy carriers. This is mainly due to the limited potential of renewable energies and their comparatively low number of full load hours in Germany. This also leads to the prioritisation of direct electrification in the application sectors due to its higher efficiency.

4 Securing Sustainability

The energy scenarios usually include a share of bio-based electricity and/or fuels. Despite the high energy requirements for the production of PtL fuels, this process has clear advantages over biogenic fuels that attracted more attention in the scientific world as well as in the political sphere in many European countries. Biofuels (also referred to as biomass-to-liquid/BtL) such as Hydro-processed Esters and Fatty Acids (HEFA) are more available on the market nowadays, and licensed under ASTM as jet fuels, there are several hard limits to using them on a large-scale in the future.

Comparing the land use for needed biomass production for biofuels and the needed landuse for PtL production will lead to much lower land use factors. In Fig. 5 the achievable mileage of an Airbus A320neo by using one hectare of land for different PtL and biogenic fuel production routes is calculated. As a result, the achievable mileage per hectare land use for PtL is at least 2 to 4.6 times higher than using biogenic fuel production pathways.

In addition to energy, water is required as the basic material for electrolysis in the production of PtL. However, this water requirement is orders of magnitude smaller than for the cultivation of biomass for the same amount of hydrogen or PtL. Between 400 and 15000 times less water is needed for PtL production [8]. The use of biogenic residues is often cited as an alternative. However, the available resources are not sufficient to cover the global PtL demand. Furthermore, the available and usable resources of residual materials should be reduced through more efficient use, since large amounts of water and land are also required for their cultivation.

Covering the energy demand for the PtL production will need additional installed capacity of wind and solar power. Following by this, additional areas are needed for these installations. Of course, the amount of land needed for renewable capacity decreases with higher wind or solar supply. Therefore, regions with a high wind and solar output are particularly suitable locations for PtL production.

Avoiding water stress and land-use changes, in particular of high nature value areas, are not the only important criteria to ensure a sustainable energy system based on 100% renewable electricity and climate-neutral PtX. Further ecological and social minimum criteria related to resource efficiency and social development should be ensured in the short-term, but should go further in their ambition in the long run by making substantial contributions to these dimensions. On behalf of the PtX Lab Lausitz, LBST and ifeu-institute developed a vision for short- und long-term PtL sustainability standards with a set of criteria and indicators respectively [12].

5 Summary

Power-to-Liquid processes are able to connect the energy and the mobility sector. Especially, for the transformation of sectors which can not be electrified directly, like aviation and maritime transport, this is a suitable option for defossilisation. Currently, it is possible to substitute 50 per cent of fossil by synthetic kerosene, presupposing it was made via the Fischer-Tropsch route.

In theory, for the production of synthetic PtL fuels between 2.5 and 5 times more energy is needed compared for the direct electric use, but in some mobility sectors direct electric use is technically not state of the art. Through a consistent and accelerated expansion of renewable energies, they make a significant contribution to avoiding additional CO_2 emissions. For a sustainable transformation of all energy sectors, however, their use must be prioritised in order to use existing resources efficiently. Particularly in international aviation and maritime transport, the use of PtL is necessary to achieve the goal of CO_2 neutrality.

Substituting all fossil by synthetic kerosene leads to an energy demand of 1.253 TWh in the European Union. A positive effect for climate can only be realized, if the needed energy is produced by renewable energies. Avoiding negative effects for climate and renewable targets, these capacities must be installed additional.

PtL Production can support the whole energy system if the operation is realized in a flexible way. Especially the hydrogen production can be operated at times with renewable energy excess in the grid. These times will increase if the amount of renewables will increase also and will reach 100 per cent. In the latter case, a flexible PtL production is able to stabilise the grid by up and down regulation of the production. This very useful function of PtX products should be considered more often in energy scenarios and investigated more intensively.

6 Disclaimer

The content of this article reflects solely the position of the authors.

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