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LOW CARBON ENERGY OBSERVATORY

ADVANCED ALTERNATIVE FUELS Technology market report

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Contact information

Name: Adrian O'CONNELL
Address: European Commission, Joint Research Centre, Ispra, Italy
Email: Adrian.OCONNELL@ec.europa.eu

Name: Maria GEORGIADOU
Address: European Commission DG Research and Innovation
Email: Maria.GEORGIADOU@ec.europa.eu

Name: Thomas SCHLEKER
Address: European Commission DG Research and Innovation, Brussels, Belgium
Email: Thomas.SCHLEKER@ec.europa.eu

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Foreword about the Low Carbon Energy Observatory

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following report series:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports

Commission staff can access all the internal LCEO reports on the Connected [LCEO page](#). Public reports are available from the Publications Office, the [EU Science Hub](#) and the [SETIS](#) website.

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Abstract

This Technology Market Report for Advanced Alternative Fuels has been carried out on behalf of the Commission by the Germany-based contractor LBST. Their deliverables under the contract were a report and a database, the report is included in the Annex.

The JRC team in charge of the technology development assessment of Advanced Alternative Fuels has subsequently summarised the findings of the LBST investigations herewith. Moreover, the results of the JRC-EU-Times model concerning the Market Outlook of Advanced Alternative Fuels are briefly presented

1 Introduction

1.1 Scope and basis of the report

The aim of the present deliverable in the framework of the LCEO is to present a market report on Advanced Alternative Fuels. The report notes both recent developments in this area thus providing an up-to-date snapshot of their market status, and it explores the likely longer term perspectives (to 2030) for these technologies. Part of their analysis provides an idea of how the market status of these various technologies are in the EU compared to the rest of the world.

1.2 Introduction to subcontracted study

The company LBST was selected as a subcontractor to provide a complete picture of the recent market status and development trends in the advanced alternative fuels technologies sector, both in Europe and globally. The main tasks LBST has undertaken were to:

- Provide a concise description of recent market trends and technology deployment including for the pathways specified in Table 1, both in Europe and globally
- Compile a database in the form of an Excel file listing significant major active companies and industrial players
- Compile a database in the form of an Excel file listing significant demonstration projects currently running or in development, and of the first-of-kind commercial systems for the sub-technology pathways identified in Table 1.
- Provide a concise assessment of the market outlook for future developments for the same technology pathways, both in Europe and globally. The outlook time horizon was for the near and medium term (i.e. up to 2030), and included a consideration of barriers to future technology development and market uptake
- Provide a concise assessment of the qualitative and quantitative information on existing support mechanisms/incentives and support policies aimed at promoting both R&D and corporate investments for advanced biofuels (and by sub-technology whenever possible), both in the EU and globally

1.3 Technologies considered

The technologies considered in this work are summarised in Table 1. A detailed description of the majority of these individual technologies can be found in the associated Technology Development Report on Advanced Alternative Fuels; LCEO deliverable D2.2.14 (2018). Also chapter 2 of the LBST report and its associated technology overview sub-sections gives more details on the technologies (LBST, 2019).

It is outside the scope of this work to look in detail at H₂, particularly its use in fuel cells etc. This report looks at the use of H₂ (and CO₂) as feedstocks to make other fuels. H₂ is of course an important fuel in its own right, and interested parties are directed to the extensive 'Fuel Cells and Hydrogen' LCEO TDR, D2.1.13 and the large "Fuel Cells & Hydrogen Joint Undertaking" resource (FCHJU, 2019) for further information.

Table 1 Alternative fuels conversion pathways and sub-technologies: source LBST (2019)

Technologies
1. Power to fuel (electrofuels)
a. H ₂ production using renewable electricity (However dedicated hydrogen production out of scope)
b. Alkaline electrolysis
c. Solid-oxide electrolysis cell (SOEC)
d. PEM (Proton exchange membrane) electrolysis
e. Water-splitting/artificial photosynthesis
f. Fuels (methanol, synthetic petrol or diesel, methane)
2. CO₂ based fuels using, recycled carbon fuels
a. Waste high concentration CO ₂ from renewable sources
b. Amine-based post combustion capture
3. Microbial fermentation
a. Industrial off-gases processed by bacteria into ethanol
b. Mixture of sewage gas and natural gas processed by bacteria into ethanol

In addition to the above fuels considered by LBST, an overview of the status of ammonia-based fuels, and of their possible market position, if any, was requested. Ammonia as a fuel is of interest as its carbon free (containing nitrogen and hydrogen), has an established transport network and can be used directly as a fuel (with some technical issues) (Valera-Medina et al, 2018). It is chiefly made from natural gas. Of the ~ 150 million tonnes of ammonia made each year, approximately 83% goes to make fertilizers for agriculture (Alkusayer et al, 2015).

2 Technology Trends and Prospects

2.1 Supportive legislation for advanced alternative fuels

At present, it could be said that corresponding incentives and support policies in most cases do not directly address advanced alternative fuels but rather provide a general framework for reducing the emissions of the transport sector. The most important piece of legislation at EU level, the recast of the Renewable Energy Directive (EU) 2018/2001 (RED II), extending the current Renewable Energy Directive from 2009 and Fuel Quality Directive beyond 2020, targets a share of renewable energy within the final consumption of energy in the transport sector of at least 14% by 2030. In the RED II, the electrofuels addressed in this report are included in the so-called “renewable liquid and gaseous transport fuels of non-biological origin”, as their energy content is derived from renewable sources other than biomass. Their renewable nature depends on the source of the electricity used for their production and Article 27 of the RED II outlines how this is to be taken into account. The waste-stream based fuels considered here are covered by the “recycled carbon fuels” category of the RED II. Both renewable liquid and gaseous transport fuels of non-biological origin and recycled carbon fuels are explicitly covered in their contribution towards the renewable energy goals of the transport sector. However, while renewable liquid and gaseous transport fuels of non-biological origin shall be taken into account by Member States in calculating the renewable energy share in transport, this is only optional for recycled carbon fuels (see RED II Articles 25 and 27). Outside the EU territory, there are not significant legislative initiatives supporting advanced alternative fuels. One exception is China which is promoting electric mobility for road transport under the scheme for so called New Energy Vehicles.

2.2 Technology, Market and Commercial Readiness of different pathways

A summary of the Technology, Market and Commercial Readiness Level of the different pathways of different advanced alternative fuels is given in Table 2. The pathways are classified according to the fuel produced in 6 categories: Power-to-Liquid (PtL), Power-to-methanol (PtCH₃OH), Power-to-methane (PtCH₄), Artificial photosynthesis, Bio-EtOH, CO₂ capture. It should be noted that CO₂ is not a fuel production pathway in itself, but it was highlighted as it's such an important part of the other pathways that intend to use captured CO₂. The same principle applies in the case of artificial photosynthesis, unless H₂ is considered as a final fuel.

According to the findings of the present study, the Technology Readiness Level of the advanced alternative fuels included varies from 2 (where the technology concept is formulated) to 9 (actual system proven in operational environment). Respectively, Market Readiness Level and Commercial Readiness Level range from 1 to 6 proving that most of these technologies are not yet commercial and mature enough to penetrate the market. An explanation of the different Technology, Market and Commercial Readiness Levels and their alignment can be found in Table 3. It is noteworthy that despite the technological maturity of some of the technologies, the commercial readiness is still low. For example, the ‘methanol route with high temperature electrolysis’ pathway presents a TRL 9 whereas its CRL is at ≥ 2 . This finding proves that commercial deployment does not depend only on the technological maturity of a given technology but also on the market structure, the investments on new plants, the existence of supportive legislation and the potential financial incentives or financial instruments.

Table 2 Technology, market and commercial readiness of different pathways (Source: LBST, 2019)

Fuel	Pathway	TRL	MRL	CRL
PtL	Fischer-Tropsch route with low temperature electrolysis	6 (RWGS ¹)	3	1
	Fischer-Tropsch route with high temperature electrolysis	6 (SOEC ² ,	3	1
	Methanol route with low temperature electrolysis	RWGS) 6-9 (DAC ³)	≥5	≥2
	Methanol route with high temperature electrolysis	6 (SOEC ⁴)	3	1
PtCH ₃ OH	Methanol synthesis with low temperature electrolysis	6-9 (DAC)	≥5	≥2
	Methanol synthesis with high temperature electrolysis	6 (SOEC)	3	1
PtCH ₄	Catalyt. methanation with low temperature electrolysis	6-9 (DAC)	≥5	≥2
	Catalyt. methanation with high temperature electrolysis	6 (SOEC)	3	1
	Biolog. methanation with low temperature electrolysis	8 (bioreactor)	5	2
	Biolog. methanation with high temperature electrolysis	6 (SOEC)	3	1
Artificial Photo-synthesis.	Hydrogen from photo-catalysis (PEC)	2-5	≤2	≤1
	Direct methanation using PEM electrolyser	2	-	-
Bio-EtOH*	Microbial fermentation of industrial off-gases	9	6	3
	Microbial fermentation of sewage gases and methane	n.d.a.	n.d.a.	n.d.a.
CO ₂ capture	CO ₂ extraction from biogas upgrading plants	9	6	6
	CO ₂ extraction from flue gas with MEA ⁵	9	6	6
	CO ₂ extraction from flue gas with K ₂ CO ₃ + electro dialysis	4	1	-
	CO ₂ extraction from flue gas with adsorption/desorption	6	3	1
	CO ₂ extraction from air with absorption/electro dialysis	4	1	-
	CO ₂ extraction from air with absorption/calcination	5	2	-
	CO ₂ extraction from air with adsorption/desorption	6	3	1
	CO ₂ liquefaction and storage	9	6	6

* Bio-EtOH refers to bio-ethanol, however strictly speaking the fermentation of industrial off-gases that are fossil in origin does not produce a biofuel, whereas the fermentation of other gases that could include a fraction of sewage gas would at least be partially bio.

¹ Reverse water gas shift

² Solid oxide electrolysis cell

³ Direct air capture

⁴ Solid oxide electrolysis cell

⁵ Mono-ethanolamine

Ammonia overview

The production and storage of ammonia are both fully commercial, with a current annual market size of over 150 million tonnes across the globe (Alkusayer et al, 2015). However this production comes from fossil feedstocks, and its end use is principally in fertilizer production.

Alternative methods for its production, and its use as a fuel, are not as developed. Care would have to be applied with respect to both its handling and storage⁶, as it is caustic, hazardous, and toxic if inhaled. With regards to an alternative production method, researchers found a cyanobacteria-based process was optimal (Angeles et al, 2018). In a significant review into the science and technology of ammonia combustion, Kobayashi et al (2019) note technical issues (namely low flammability and high NO_x production) which must be overcome in order for its direct use as a fuel to grow. Afif et al (2016) in a comprehensive review of the use of ammonia in next-generation fuel cells stated that it is promising, but such technology is not yet at a commercially ready stage.

⁶ FAO, Safety operation of anhydrous ammonia equipment. <http://www.fao.org/3/y1936e/y1936e0f.htm>
LCE0 Advanced Alternative Fuels Technology Market Report 2018

Table 3 Technology, Market and Commercial Readiness Levels (Source: LBST, 2019)

Description TRL	TRL	MRL	CRL
Basic principles observed	1	-	-
Technology concept formulated	2	-	-
Experimental proof of concept	3	-	-
Technology validated in lab	4	1	-
Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	5	2	-
Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	6	3	-
System prototype demonstration in operational environment	7	4	1
System complete and qualified	8	5	2
Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	9	6	3
Multiple commercial applications becoming evident locally although still subsidised. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions.	-	-	4
Market competition driving widespread deployment in context of long-term policy settings. Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring.	-	-	5
'Bankable' grade asset class driven by same criteria as other mature energy technologies. Considered as a 'bankable' grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake.	-	-	6

2.3 JRC Overview: R&D investment and patenting activity

Advanced Alternative Fuels are still in their infancy relative to other fuels such as fossil or biofuels. Therefore, as far as we know no (sufficiently) detailed information on R&D and patenting activities specific to these fuel production pathways is available. JRC searches (Fiorini et al, 2017, Pasimeni et al, 2018) of patents showed several entities with projects involving synthetic fuels had registered patents, but these were very small in number. Indeed the particular subset of the JRC's work which had been investigated had been looking more at biofuel patents as opposed to those for advanced alternative fuels. There are certainly a large number of hydrogen patents. While their focus is unlikely to be on the use of H₂ for further fuel synthesis, they show the large scale of interest in H₂ in general. And while H₂ itself is outside the main focus of this work, it's likely any advances in technologies surrounding this "feedstock" - for e.g. in its production or storage - could be expected to positively impact H₂-using advanced alternative fuel pathways.

R&D and patenting activities on CO₂ capture are discussed in the 2018 LCEO Technology Market Report D4.2.9 dedicated to Carbon Capture, Utilisation and Storage (LCEO, 2018b).

3 Market Overview

3.1 EU position in the global market

As already mentioned, most of the technologies assessed in the frame of this report are at demonstration scale and present at the moment a very low CRL. Therefore, an established market does not really exist (with the exception of the purification of biogas to make bio-methane) and isn't likely to be developed in the near future (see also subchapter 4.3 of the present document). Only 3 pathways for the capture of CO₂, namely 'extraction from biogas upgrading plants', 'extraction from flue gas with MEA' and 'CO₂ liquefaction and storage', have a CRL6. In 2017 the total capacity of upgrading plants including pressurized water scrubbing (PWS) and membrane technologies in the EU amounted to about 170,000 Nm³ of methane per hour. Of these, about 70,000 Nm³ of methane per hour is available from technologies which can supply CO₂ with a sufficiently high purity for further fuel synthesis. Some alternative fuel concepts are based on environmental CO₂ concentrations but these are lab-scale or pilot-plant scale. Concerning power to methane, almost all plants are installed in the EU (11 plants with a capacity of about 7MW of CH₄ by the end 2018). Including plants under construction, planned, and announced plants the capacity could reach more than 16 MW of CH₄. Typically the CO₂ used in these plants is obtained from biogas. Concerning power-to-methanol, there are only a few existing and projected installations in the EU (which is a pioneer in the field) with a total capacity of almost 800 kW. As far as power-to-liquid plants for the production of petrol, kerosene, and diesel are concerned, the current capacity in the EU is 150 kW.

4 Market Outlook

4.1 Barriers

Advanced alternative fuels will be competing with other low or zero emission options in transport on availability and total cost basis. The cost of electrofuels is mainly driven by the underlying cost of electricity. In all European countries, various taxes and levies constitute a significant share of the electricity price. As a result, the question of which of these taxes and levies apply in what way when using renewable electricity to produce electrofuels is a decisive factor for the cost and resulting competitiveness of an advanced fuel (LBST, 2019). Electricity pricing may be lower if grid electricity is used, but this would have a higher GHGi than renewable electricity – and thus the resulting alternative fuel would have a high GHGi – therefore it would likely be impractical.

4.2 Conversion technology supply from EU to global markets

The following section aims to briefly describe the likelihood of conversion technology supply from the EU to global markets, i.e. to try and put into context the level of EU leadership on advanced alternative fuel production technologies compared to worldwide players.

The vast majority of advanced alternative fuel plants found and discussed in this report are power-to-x or electrofuel plants (LBST, 2019), and most are situated in Europe (Schmidt et al, 2018). LBST (2019) also acknowledge that for electrofuels in Europe, prototype deployment is certainly happening, but outside Europe activities are considered to be still in “their infancy”. Of the various electrofuel categories, power-to-gas projects are the most prevalent, and these too are again mainly EU based (with some projects in North America) (Thema et al, 2019). Reviewing the database provided by LBST on major companies or industrial players actively investigating advanced alternative fuel production (which includes a consideration of plants), the dominance of EU-based companies can be seen; of the 219 projects, 88% are in the EU, 7% in non-EU Europe and 5% in North America. These EU companies are developing and working with their own technologies, i.e. technologies created in-house, as opposed to relying on outside expertise. So while the EU appears well positioned to market its conversion technologies to areas outside the EU, it’s worth noting the principle issue hindering the market development of electrofuels according to LBST is in fact not technical, but due to costs - mainly the underlying cost of the electricity. And that is an issue somewhat outside of the control of the fuel conversion technology developers.

4.3 JRC-EU-Times Model results

The JRC-EU-TIMES model offers a tool for assessing the possible impact of technology and cost developments. It represents the energy system of the EU28 plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050.

The model was run with three global storylines:

- **Baseline:** continuation of current trends; it represents a ‘business as usual’ world in which no additional efforts are taken on stabilising the atmospheric concentration of GHGs; only 48 % CO₂ emissions reduction by 2050.

- **Diversified:** usage of all known supply, efficiency and mitigation options (including CCS and new nuclear plants); CO₂ emissions reduction target of 80 % is achieved by 2050.
- **ProRES:** same as diversified scenario in terms of CO₂ emissions reduction target by 2050 but there are no new nuclear plants and no underground storage of CO₂ (no CCS).

For the decarbonised scenarios (Diversified and ProRES), sensitivities have been designed with different assumptions on the technology learning, the use of resources and policies (see Figure 1). Detailed information on the features of the model and all scenarios can be found in deliverable report D4.7 prepared by the JRC-EU-TIMES modelling team (Nijs et al., 2018).

In summary, sensitivities on technology learning assume lower or higher learning rates in LowLR and HighLR scenarios respectively and the achievement of SET Plan targets in the Res4_SET scenario. Two more sensitivities include more optimistic assumptions for the CAPEX of Direct Air Capturing (Div4_DAC and Res5_DAC scenarios).

In terms of resources, sensitivities have been run assuming cheaper fossil fuels (CheapFossil scenario) or a higher forestry biomass potential (HighForest scenario).

At the policies level, two specific sensitivities restrict CCUs: in the Div6_NoCC_InPower scenario, carbon capture is not deployed in the power sector, while in the Res8_NoCCU scenario, the utilisation of CO₂ is restricted on top of the geological storage restriction that was already in place in the ProRES scenarios. There is also a near zero carbon energy variant of the ProRES scenario that assumes a long-term decarbonisation target of 95% below 1990 levels in 2050.

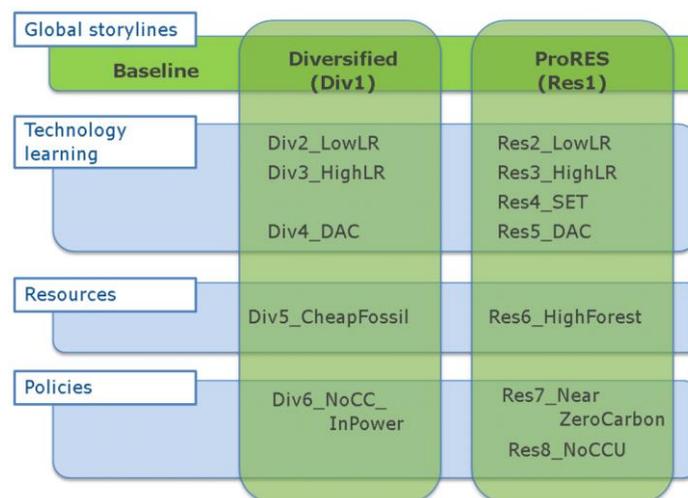


Figure 1 Overview of all scenarios and sensitivities (Source: Nijs et al., 2018)

Modelling results in terms of capacity installed and investments for the production of advanced alternative fuels used in transport from 2020 to 2050 are shown in Figure 2 and Figure 3 for the global storylines scenarios and sensitivities scenarios.

Figure 2 shows the installed capacity (in PJ) for the production of advanced alternative fuels per year (on the left axis) and the cumulative capacities (on the right axis). It is obvious from the graphs presented that these technologies are still in their infancy but they are expected to grow in the mid future. According to the model results, the installed cumulative capacity is expected to increase from near 0 PJ in 2020 to almost 70 PJ in 2050 in the baseline scenario. This increasing tendency is more intense in the diversified

scenario (from 0 PJ in 2020 to 140 PJ in 2050). All sensitivities scenarios show the same trend (see upper part of Figure 2).

Concerning the ProRES scenarios, the cumulative capacities for the production of advanced alternative fuels increase substantially from 2020 to 2050, reaching more than 1,000 PJ in 2050, most of it coming from the increased production capacity of hydrogen plants. Specifically, in the case of the NearZeroCarbon scenario, the cumulative capacity of hydrogen production plants is estimated to be over 1500 PJ.

Figure 3 shows the model results in terms of investments from 2020 to 2050 (in billion Euro) for the global storylines scenarios and sensitivities scenarios. The amount of investment shows the same trend as the installed capacities commented above. As expected the lion's share in the investments concerns hydrogen production plants.

However, it is worth noticing that all capacities and investments reported are related to technologies that produce diesel, kerosene or methane. Those e-fuels contain carbon from CO₂ that was captured. The hydrogen production only covers the feedstock to make those fuels and does not include hydrogen production for direct uses. Hydrogenation and methanation are reported separately and include the investments to convert that hydrogen and the CO₂ to e-fuels. A large share of the investments is for the production of the hydrogen feedstock. This hydrogen is produced with electrolyzers that need to have a sufficiently large capacity to transform most of the surplus or dedicated power from variable renewable sources. In contrast, for the conversion of that hydrogen into e-fuels, much less capacity is required because these processes can operate with much higher full load hours.

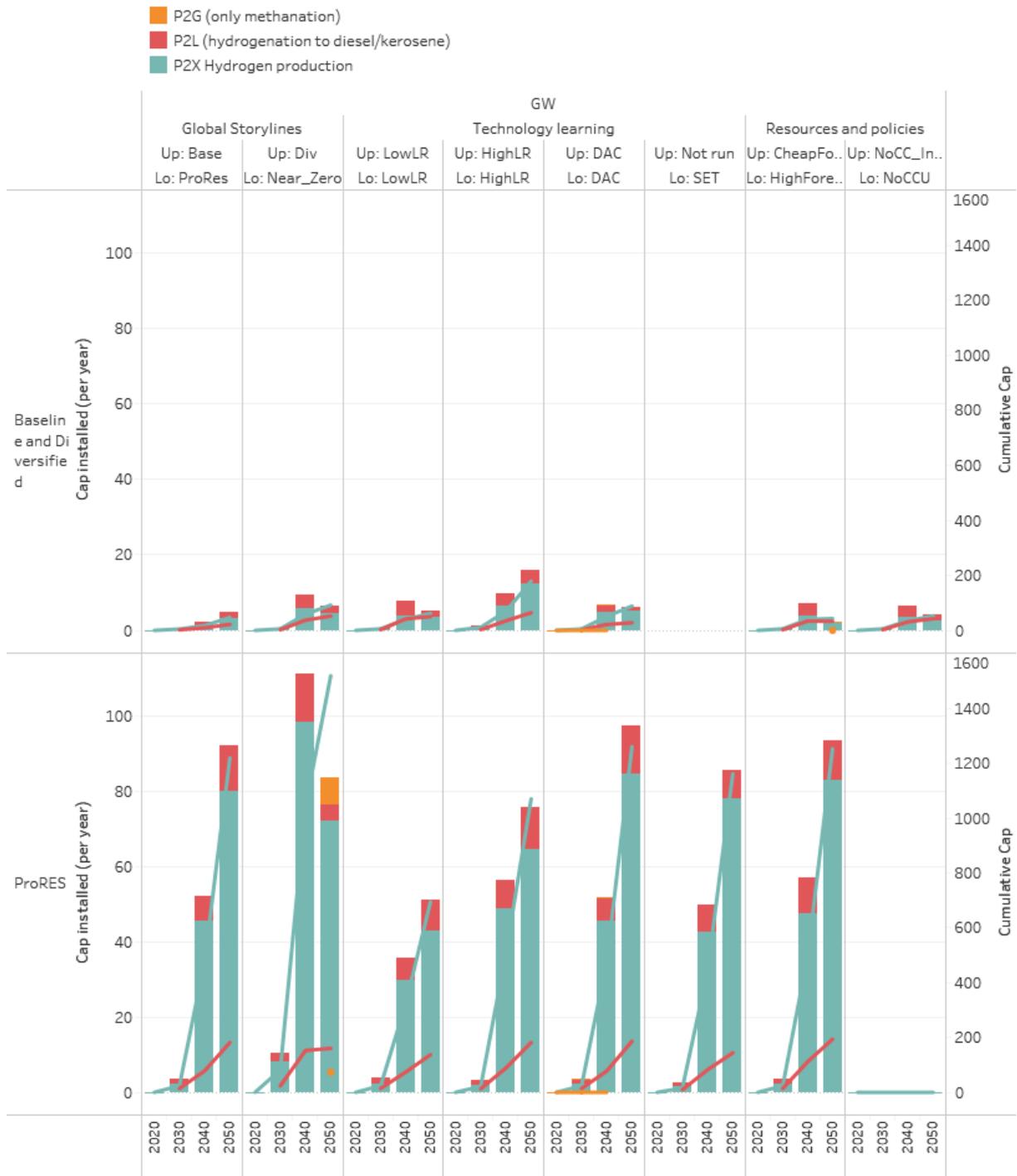


Figure 2 Installed capacities per year and cumulative capacities (in PJ) of advanced alternative fuels technologies in EU for different scenarios; hydrogen production as feedstock to make methane, diesel or kerosene (Source: JRC-EU-TIMES modelling results)

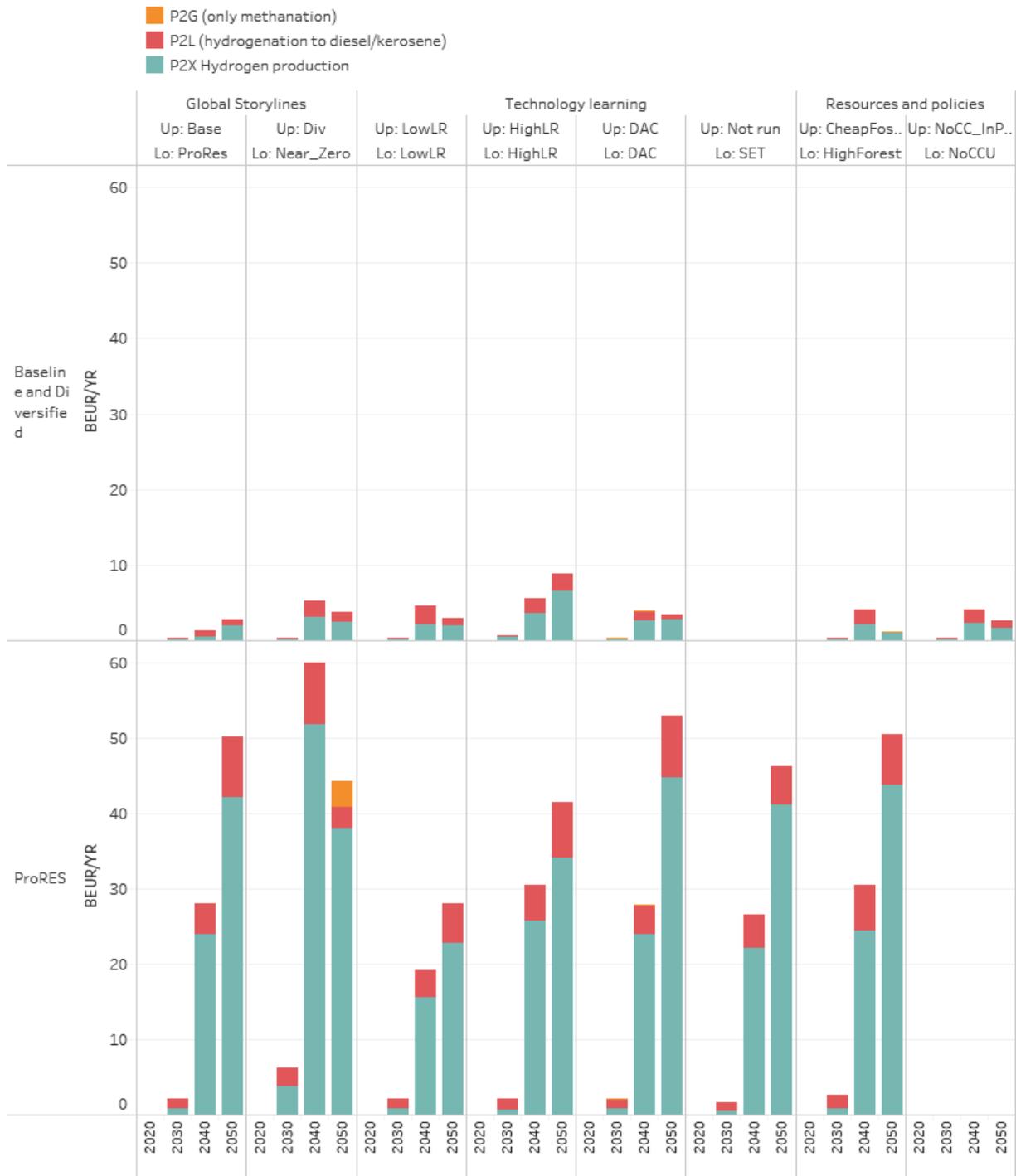


Figure 3 Total investment (billion Euro/year) in advanced alternative fuels technologies in EU for different scenarios; hydrogen production as feedstock to make methane, diesel or kerosene (Source: JRC-EU-TIMES modelling results)

5 Summary, Conclusions, Recommendations

In summary, JRC agrees with the results of the LBST (2019) study, and applauds its quality and level of detail. Regarding market status, it has been seen that most of the technologies assessed in this report are still at the demonstration scale presently and as such have a very low CRL. Furthermore, an established market doesn't really exist and is not likely to be developed at least in the near future, unless a significant drop in electricity prices can be achieved. Some sub-pathways (i.e. for the capture of CO₂) are seen to have a TRL of 6, but of course it must be remembered these are really providing part of a feedstock for final fuel production chains, as opposed to producing final fuels themselves. LBST (2019) note that while electrofuel production is seeing prototype deployment in Europe, activities outside Europe are still in their infancy.

Regarding policy support, LBST (2019) highlighted that in the EU, both renewable liquid and gaseous transport fuels of non-biological origin (for the purposes of the fuels studied in this report are principally comprised of electrofuels) and recycled carbon fuels (mainly microbial fermentation) are explicitly covered in their contribution towards the renewable energy goals of the transport sector. They note renewable liquid and gaseous transport fuels of non-biological origin shall be taken into account by Member States in calculating their renewable energy share in transport, while such action is only optional for recycled carbon fuels. They note there are no relevant policies supporting advanced alternative fuels as covered in their report outside of Europe.

LBST (2019) further consider it likely, given the growth in renewable electricity, that more power-to-x pathways will appear in the future, although the degree to which that will occur remains unclear. A similar trend of future growth in power-to-x fuels (i.e. with more H₂ production from renewable power) is seen in the JRC EU Times model. Although it is worth reiterating that this report did not consider H₂ as a final fuel in itself, but rather considered it's growing importance as a feedstock (to be combined with carbon) thus making other final fuels.

Regarding pathways with low TRL, the report notes they will be able to benefit from European as well as national R&D grants (thus hopefully helping improve their TRL and helping them get closer to eventually having a market presence). However the report cautions that such fuels will be competing with other low or zero emission options in transport on availability and cost on a total cost of ownership basis. The vast majority of advanced fuels considered in this report fall into the electrofuels category, whose cost is mainly driven by the cost of the electricity used as their 'feedstock'. In the EU, different taxes and levies make up a large share of the electricity price. LBST (2019) conclude by saying how these taxes and levies apply when using renewable electricity to produce electrofuels will be the decisive factor for their cost competitiveness. It is also worth noting that most advanced alternative fuel projects or plants considered in this report are EU-based. This raises the possibility that EU companies could market their technologies to areas outside of the EU. This should be considered alongside the fact that the main issue with the majority of these projects is not a technical one, but is due to the cost of electricity, so this apparent EU advantage may not be as significant as initially appears.

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List of abbreviations and definitions

CCU	Carbon capture and use
CH ₄	Methane
CO ₂	Carbon dioxide
CRL	Commercial Readiness Level
DAC	Direct air capture
EtOH	Ethanol
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FT	Fischer-Tropsch
JRC	European Commission's Joint Research Centre
KW	Kilowatt
LBST	Ludwig-Bölkow-Systemtechnik
LCEO	Low Carbon Energy Observatory
LR	Learning rate
MEA	Mono-ethanolamine
MRL	Market Readiness Level
MW	Megawatt
NDA	No data available
Nm ³	Norm cubic meter
PEC	Photo-catalysis/photo-electrochemical cell
PEM	Proton exchange membrane (electrolyser, fuel cell)
PJ	Petajoules
PtL	Power to liquid
PtX or P2x	Power to X (where x can be a liquid or a gaseous fuel)
PWS	Pressurized water scrubbing
RED	Renewable Energy Directive
RoW	Rest of the World
RWGS	Reverse water gas shift
R&D	Research and Development
SOEC	Solid oxide electrolysis cell
TRL	Technology Readiness Level
US	United States

Annexes

Annex 1. LBST 2019 report and database

**REPORT ON MARKET AND INDUSTRIAL
DEVELOPMENT INTELLIGENCE FOR ADVANCED
ALTERNATIVE FUELS**



REPORT ON MARKET AND INDUSTRIAL DEVELOPMENT INTELLIGENCE FOR ADVANCED ALTERNATIVE FUELS

AN LBST ANALYSIS FOR THE JOINT RESEARCH CENTRE (JRC)

Werner Weindorf
Patrick Schmidt
Tetyana Raksha
Uwe Albrecht

FINAL
28 June 2019



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systemtechnik

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REPORT

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ACRONYMS AND ABBREVIATIONS

CH ₄	Methane
CO	Carbon monoxide
CO ₂	Carbon dioxide
CRL	Commercial readiness level
DAC	Direct air capture
DME	Dimethyl ether
EtOH	Ethanol
GHG	Greenhouse gas(es)
h	Hour(s)
H ₂	Hydrogen
kg	Kilogram
kW	Kilowatt
LBST	Ludwig-Bölkow-Systemtechnik
LCA	Life cycle assessment
LHV	Lower heating value
LT	Low temperature
MJ	Megajoule
MRL	Market readiness level
MTG	Methanol to gasoline
MW	Megawatt
Nm ³	norm cubic metre
PEC	Photo-catalysis / photo-electrochemical cell
PEM	Proton exchange membrane (electrolyser, fuel cell)
PM	Particulate matter
PSA	Pressure swing adsorption
PtCH ₃ OH	Power-to-methanol
PtCH ₄	Power-to-methane
PtG	Power-to-gas
PtH ₂	Power-to-hydrogen
PtL	Power-to-liquid
PWS	Pressurized water scrubbing
RWGS	Reverse water gas shift
SOEC	Solid oxide electrolysis cell
T	metric ton
TRL	Technology readiness level
TSA	Temperature swing adsorption
yr	Year

EXECUTIVE SUMMARY

The pathways investigated in this study have a wide range of technology readiness levels (TRL). A high technology readiness is a necessary prerequisite for market entry, which is represented by the performance indicator 'market readiness level' (MRL). For further differentiation of different technologies and their economic performance on the market, a 'commercial readiness level' (CRL) is included here.

Table 1: Overview over technology, market, and commercial readiness of components and pathways investigated in this study

Fuel	Pathway	TRL** [1 – 9]	MRL [1 – 6]	CRL [1 – 6]
PtL*	Fischer-Tropsch route with low temperature electrolysis	6 (RWGS)	3	1
	Fischer-Tropsch route with high temperature electrolysis	6 (SOEC, RWGS)	3	1
	Methanol route with low temperature electrolysis	8-9 (DAC)	≥5	≥2
	Methanol route with high temperature electrolysis	6 (SOEC)	3	1
PtCH ₃ OH	Methanol synthesis with low temperature electrolysis	8-9 (DAC)	≥5	≥2
	Methanol synthesis high temperature electrolysis	6 (SOEC)	3	1
PtCH ₄	Catalyt. methanation with low temperature electrolysis	6-9 (DAC)	≥5	≥2
	Catalyt. methanation with high temperature electrolysis	6 (SOEC)	3	1
	Biolog. methanation with low temperature electrolysis	8 (bioreactor)	5	2
	Biolog. methanation with high temperature electrolysis	6 (SOEC)	3	1
Artificial photosy.	Hydrogen from photo-catalysis (PEC)	2-5	≤2	≤1
	Direct methanation using PEM electrolyser	2	–	–
Bio-EtOH	Microbial fermentation of industrial off-gases	9	6	3
	Microbial fermentation of sewage gases and methane	n. d. a.	n. d. a.	n. d. a.
CO ₂ capture	CO ₂ extraction from biogas upgrading plants	9	6	6
	CO ₂ extraction from flue gas with MEA	9	6	6
	CO ₂ extraction from flue gas with K ₂ CO ₃ + electrodialysis	4	1	–
	CO ₂ extraction from flue gas with adsorption/desorption	6	3	1
	CO ₂ extraction from air with absorption/electrodialysis	4	1	-
	CO ₂ extraction from air with absorption/calcination	5	2	-
	CO ₂ extraction from air with adsorption/desorption	6	3	1
	CO ₂ liquefaction and storage	9	6	6

* Methanol, gasoline, kerosene, diesel;

** Performance determining processes are indicated in brackets;

RWGS = reverse water gas shift; SOEC = solid oxide electrolysis cell; DAC= direct air capture of CO₂;

PEC = photo-catalysis or photo-electrochemical water splitting; n. d. a. = no data available

1 INTRODUCTION, MOTIVATION AND METHODOLOGY

Increasing European transport volume lead to growing energy demand as well as to environmental and climate challenges. In addition to improving vehicle efficiency and shifting transport to more environmentally friendly transport modes (public transport, transport of goods via train), increasing the share of renewable energy used for transport is a key element in the European energy and climate strategy. While using renewable electricity in battery electric and fuel cell electric drive trains provide the highest energy efficiency and is, therefore, expected to be the prime choice in many transport applications, advanced alternative fuels based on synthetically produced 'green' hydrocarbons using atmospheric or otherwise captured carbon dioxide may also play a relevant role in the future.

The report provides comprehensive information on the up-to-date market status and likely development trends until 2030 for selected advanced alternative fuel technologies, giving an indication on which of these technologies are more likely to become commercial in the future.

Table 2 shows the alternative fuels conversion pathways and sub-technologies to be included in the report. Further technologies will be added in the course of the analysis where appropriate.

Table 2: Alternative fuels conversion pathways and sub-technologies included in this report

Technologies
1. Power to fuel (electrofuels)
a. H ₂ production using renewable electricity
b. Alkaline electrolysis
c. Solid-oxide electrolysis cell (SOEC)
d. PEM (Proton exchange membrane) electrolysis
e. Water-splitting/artificial photosynthesis
f. Fuels (methanol, synthetic petrol or diesel, methane)
2. CO₂ based fuels using, recycled carbon fuels
a. Waste high concentration CO ₂ from renewable sources
b. Amine-based post combustion capture
3. Microbial fermentation
a. Industrial off-gases processed by bacteria into ethanol
b. Mixture of sewage gas and natural gas processed by bacteria into ethanol

2 MARKET OVERVIEW

2.1 Definition of various readiness levels

The technology readiness level (TRL) describes the maturity of a technology. The market readiness level (MRL) correlates with the TRL. Furthermore, the commercial readiness level (CRL) can be applied.

Table 3 shows the TRL according to [Horizon 2020], the associated MRL according to [Muradovich 2017] and the associated CRL.

Table 3: Technology Readiness Level (TRL) and Market Readiness Level (MRL)

Description TRL	TRL	MRL	CRL
Basic principles observed	1	–	–
Technology concept formulated	2	–	–
Experimental proof of concept	3	–	–
Technology validated in lab	4	1	–
Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	5	2	–
Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	6	3	–
System prototype demonstration in operational environment	7	4	1
System complete and qualified	8	5	2
Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	9	6	3
Multiple commercial applications becoming evident locally although still subsidised. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions.	–	–	4
Market competition driving widespread deployment in context of long-term policy settings. Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring.	–	–	5
'Bankable' grade asset class driven by same criteria as other mature energy technologies. Considered as a 'bankable' grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake.	–	–	6

Figure 1 shows the overlap between TRL and CRL.

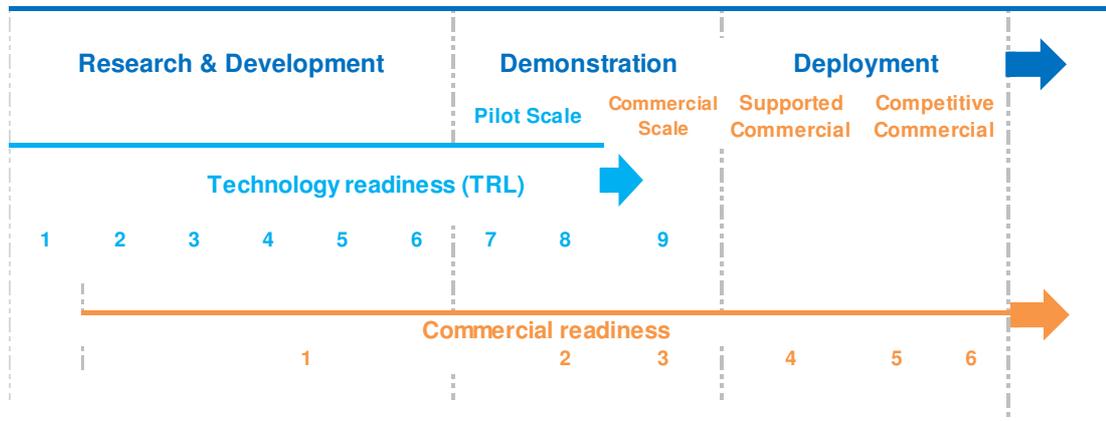


Figure 1: Overlap between TRL and CRL

2.2 Taxonomy and definitions

2.2.1 Power-to-X (PtX)

The concept of power-to-X comprises a range of electricity-based fuels (sometimes also referred to as e-fuels) and their application in various sectors (power-to-heat, power-to-fuel, power-to-chemicals, etc.). This has resulted in a range of wordings that resemble different sets and sub-sets of power-to-X aspects. In [Bünger et al. 2017], a taxonomy for the power-to-X family of terms and key processes has been developed as depicted in Figure 2.

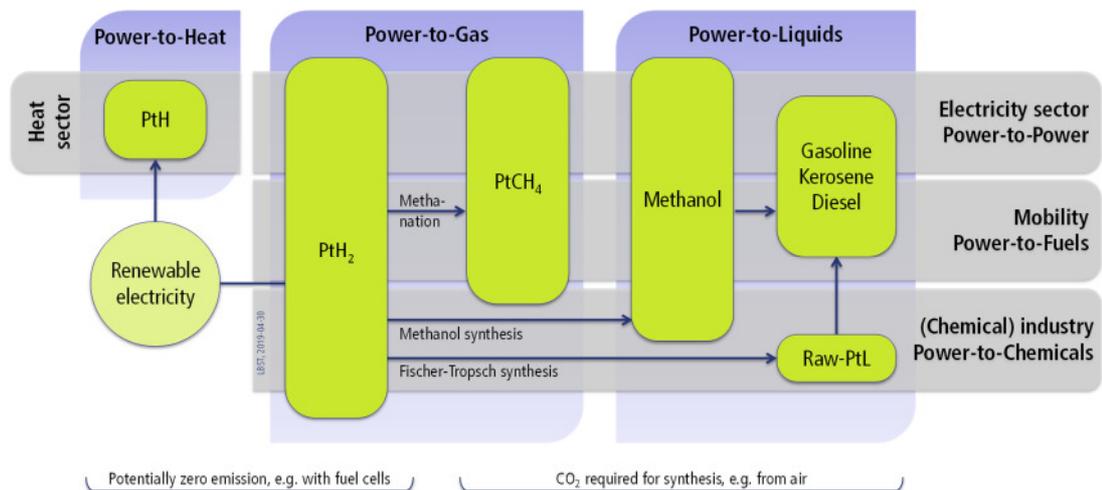


Figure 2: Power-to-X (PtX) family of terms and key processes (graphic: LBST adapted from [Bünger et al. 2017])

With the exception of power-to-heat (PtH), all PtX pathways depicted in Figure 2 comprise a chemical energy carrier.

2.2.2 Artificial photosynthesis

'Artificial photosynthesis', 'biological photosynthesis', 'biomimetic processes', 'hybrid systems' and 'power-to-x' are just a few of many wordings used to cluster fuel conversion processes from renewable (biomass and non-biomass based) and sometimes also non-renewable sources. In a current publication by [acatech et al. 2018] the following definitions are suggested:

- « • *[Modified] biological photosynthesis: fuels and valuable products are produced by [genetically engineered] photosynthetic microorganisms. [...]*
- *Combining biological and nonbiological components to create **hybrid systems**: This makes use of renewably generated electricity for the electrolytic production of hydrogen and carbon monoxide which are converted into fuels and valuable products by microorganisms in bioreactors.*
 - ***Power-to-X** technologies: These processes use electricity from renewable sources [...] for the electrochemical synthesis of fuels or valuable products. These include, for instance, hydrogen, ethylene or, in multistage processes, methane (natural gas), alcohols or hydrocarbon-based plastics.*
 - ***Artificial photosynthesis**: solar energy is converted with the assistance of catalytic processes and used for producing fuels and valuable products. Production takes place in completely integrated systems such as for example "artificial leaves" or by directly combining photovoltaic and electrolysis systems. »*
- Source: [acatech et al. 2018]

The definitions result in a taxonomy as depicted in Figure 3.

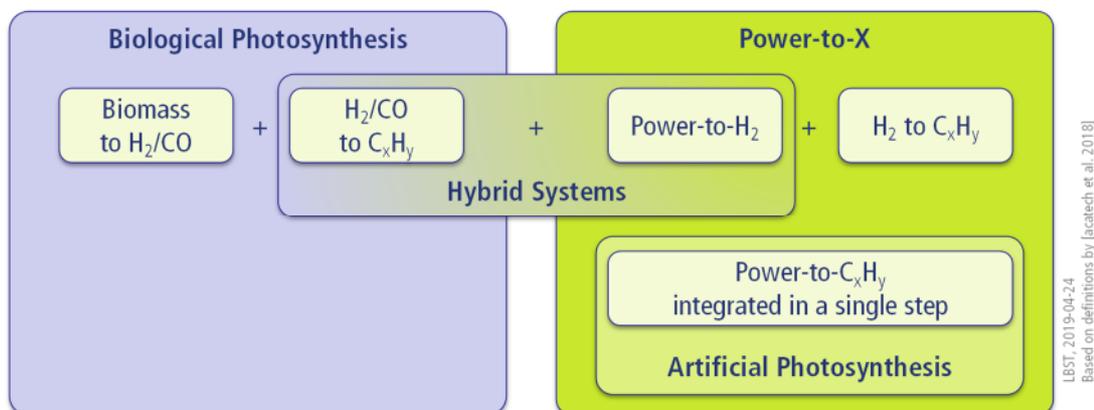


Figure 3: Taxonomy of artificial photosynthesis (graphic: LBST)

2.3 CO₂ capture for fuel production

2.3.1 CO₂ from biogas upgrading plants

The CO₂ content of biogas ranges between 25 and 55% [Eder & Schulz 2006]. The CO₂ can be separated from the biogas stream via scrubbing with amines, via pressure swing adsorption (PSA), or via cryogenic processes. All these technologies provide sufficient CO₂ purity (>99%). Further technologies are pressurized water scrubbing (PWS). However, PWS does not provide sufficient CO₂ purity. Cryogenic processes can supply very pure CO₂ and includes CO₂ liquefaction (see chapter 2.3.4).

Both biogas upgrading via scrubbing with amines and biogas upgrading via PSA are technically mature (TRL = 9). Many plants have been installed worldwide for the upgrading of biogas for injection into the natural gas grid. The technology is commercially available and (CRL = 6, MRL = 6).

In 2017 about 830 million Nm³ (29.7 PJ based on the LHV or about 1% of the natural gas consumption in Germany) of upgraded biogas has been injected into the natural gas grid in Germany [BNA & BKA 2019]. In Germany, there are more than 200 biogas upgrading plants with a capacity of about 120,000 Nm³ of methane per hour [dena 2019].

Table 4 shows the electricity consumption of biogas upgrading via scrubbing with amines, PSA, and cryogenic processes, the existing installed capacity of these technologies in the EU, and the potential PtCH₄ capacity from these plants. The electricity consumption has been derived from [KTBL 2012] and the installed capacity has been derived from [Biogaspartner 2019]. In 2017 the total capacity of upgrading plants including PWS and membrane technologies in the EU amounted to about 170,000 Nm³ of methane per hour. Thereof, about 70,000 Nm³ of methane per hour come from technologies which can supply CO₂ with a sufficiently high purity.

Table 4: CO₂ from biogas upgrading and potential PtCH₄ capacity from today's installed capacity in the EU

		Scrubbing with amines	PSA	Cryogenic processes
Electricity consumption	kWh/Nm ³ _{biogas}	0.29	0.90	0.92
	kWh/Nm ³ _{CO₂}	0.69	2.14	2.19
	kWh/kg _{CO₂}	0.35	1.09	1.11
Heat consumption	kWh/Nm ³ _{biogas}	2.16	-	-
	kWh/Nm ³ _{CO₂}	5.14	-	-
	kWh/kg _{CO₂}	2.62	-	-
Methane slip		0.1%	3.0% ^{**}	n. d. a.
	Nm ³ CH ₄ /h	42730	24932	0
Installed capacity EU in 2017	Nm ³ biogas/h	73672	42986	0
	Nm ³ CO ₂ /h	30942	18054	0
	t CO ₂ /h	37	22	0

		Scrubbing with amines	PSA	Cryogenic processes
Potential for PtCH ₄	Nm ³ CH ₄ /h	30942	18054	0
	MW _{CH₄}	308	180	0

*CO₂ content: 42% by volume; **Used in a lean gas burner; n. d. a.: no data available

Alternatively, if methane is the desired product the biogas stream including the CO₂ is directly fed into the methanation reactor together with the hydrogen ('direct methanation') [Rieke 2013]. The CO₂ fraction is converted to methane. The methane gas is swept through the methanation reactor like an inert gas. In this case no CO₂ separation step is required.

2.3.2 CO₂ from flue gas

State-of-the-art is the extraction of CO₂ from flue gas via scrubbing with amines e.g. monoethanolamine (MEA). The scrubbing agent washes out the CO₂ from the gas stream. The scrubbing agent is regenerated via heating up. The technology can be considered as mature (TRL = 9).

Another process is described in [Taniguchi et al., 2014]. At first the CO₂ is washed out from the gas stream via scrubbing with K₂CO₃ solution. Then, the CO₂ concentration in the scrubbing agent is elevated via electro dialysis and then stripped out by a vacuum pump. The process is at an early stage of research and development (TRL = 4).

A process described in [Allam et al. 2006] is based on a combination of pressure swing adsorption (PSA) and temperature swing adsorption. Pilot tests have been carried out (TRL = 6).

Table 5 shows the energy demand for various processes for the extraction of CO₂ from flue gases. The CO₂ concentration of the flue gas amounts ranges between 10 and 13%.

Table 5: Processes for the extraction of CO₂ from flue gases, e.g. from biomass combustion or industrial processes

	Unit	MEA	'Next Generation Solvent'	Absorption/ electro dialysis	PSA/TSA
CO ₂ content	-	12.8%	11%	10%	10-13%
Heat	MJ/kg _{CO2}	3.84-4.30	n. d. a.	-	n. d. a.
Electricity	MJ/kg _{CO2}	0.033	n. d. a.	0.756	n. d. a.
Total	MJ/kg _{CO2}	3.873-4.333	2.5	0.756	2.016
T (heat)	°C	97	120	-	n. d. a.
Reference		[Socolow et al. 2011], [ZSW 1995]	[Bergins et al. 2010]	[Taniguchi et al. 2014]	[Allam et al., 2006]

n. d. a.: no data available

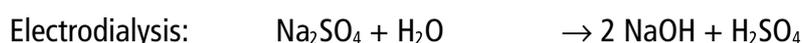
2.3.3 CO₂ from air

There are various technologies for the separation of CO₂ from air developed by various research institutes and companies.

2.3.3.1 Scrubbing/Electrodialysis

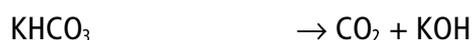
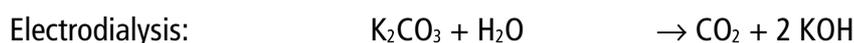
One option to extract CO₂ from the air is via scrubbing using a scrubbing agent, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), which is converted to sodium carbonate (Na₂CO₃) or potassium carbonate (K₂CO₃), respectively. The decomposition is done via electrodialysis.

The ZSW process described in [Specht et al. 1996] is based on absorption with sodium hydroxide (NaOH), stripping the CO₂ with sulphuric acid (H₂SO₄), and regeneration of the Na₂SO₄ via electrodialysis. The following reactions occur:



The specific electricity consumption depends on the current density of the electrodialysis plant. The higher the current density the higher is the specific electricity consumption. At a current density of 100 mA per cm² of electrodialysis cell area the electricity consumption for the whole process including fan blower amounts to 430 kJ per mole of CO₂ or about 9.8 MJ per kg of CO₂ [Specht et al. 1998]. [Specht, 1999] indicates an electricity consumption of about 12.3 MJ per kg of CO₂ due to a higher current density. (Sterner, 2009) indicates an energy consumption of about 8.2 MJ per kg of CO₂ for the extraction of CO₂ from air via the ZSW process (thereof 6.4 MJ/kg for the electrodialysis for regeneration of the scrubbing agent).

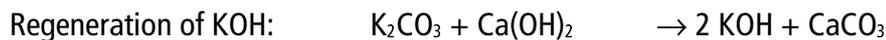
A process developed by the Palo Alto Research Center (PARC) uses KOH as scrubbing agent to separate CO₂ from air. In [Eisaman et al., 2010] a process has been described where KOH is used as scrubbing agent. The following reactions occur:



The electricity consumption is indicated with 300 kJ per mole of CO₂ (thereof 100 kJ for the electrodialysis of the KHCO₃ solution from CO₂ absorption with KOH) which leads to about 6.8 MJ per kg of CO₂.

2.3.3.2 Scrubbing/Calcination, Carbon Engineering

The process which has been developed by the Canadian company Carbon Engineering (CE) consists of CO₂ absorption with KOH, formation of CaCO₃ from K₂CO₃ and regeneration of the CaCO₃ via calcination and subsequently conversion to Ca(OH)₂. The following reactions occur:



The calcination process requires very high temperatures of more than 800°C to convert the CaCO₃ back to CaO to recover the CO₂. Carbon Engineering assumes that natural gas is used as fuel for the calcination process and for the supply of electricity for the whole process and indicates a natural gas consumption of about 10 MJ per kg of CO₂ [CE 2015]. The theoretical minimum heat requirement for the calcination reaction amounts to about 4.1 MJ per kg of CO₂.

2.3.3.3 Adsorption/Desorption cycle, Climeworks

Another option is the technology developed by the Swiss company Climeworks. Climeworks (a spinoff of the ETH Zurich) uses an adsorption/desorption cycle to extract CO₂ from the air. The CO₂ is chemically bound on a sorbent (in contrast to most adsorption processes chemisorption instead of physisorption is applied here). The regeneration of the sorbent is carried out by low temperature heat (95°C) [Climeworks 2015a]. The process can also be referred to as a temperature swing adsorption (TSA) process [Climeworks, 2015b].

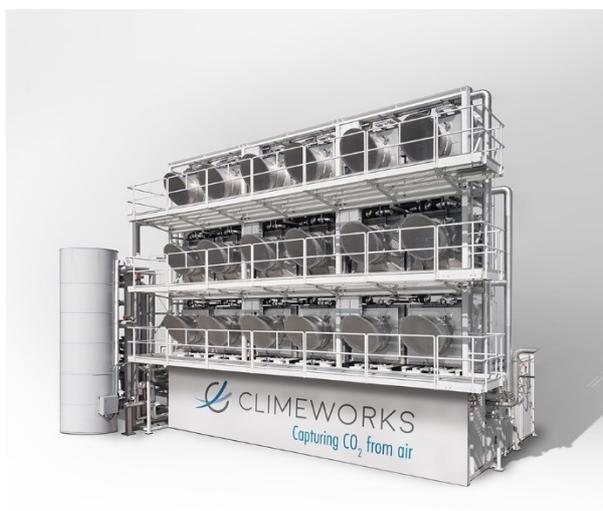


Figure 4: Direct capture of CO₂ from air (image: Climeworks 2018)

Table 6 shows the required investment for direct air capture (DAC) plants based on the Climeworks technology.

Table 6: Investment direct capture of CO₂ from air [Climeworks 2015]

Capacity (kg CO ₂ /h)	Investment (million €)*
35	0.95 – 1.43
125	1.43 – 1.90
2000	15.2
20,000	91.2

* Converted from CHF to €, exchange rate: 0.95 €/CHF

Homepage: <http://www.climeworks.com/>

This process has also been applied at the methanation plant in Troia in Apulia in Italy (as part of the Horizon 2020 research project STORE&GO, see chapter A1.9) and at Sunfire's power-to-liquid plant based on high temperature electrolysis with downstream Fischer-Tropsch synthesis in Dresden in Germany (see chapter A3.3).

2.3.3.4 Summary CO₂ capture for fuel production

Table 7 shows an overview of various technologies for the direct capture of CO₂ from air.

Table 7: Technologies for the CO₂ capture from air

	Unit	ZSW	PARC	CE	Climeworks
Technology		Absorption/ Electrodialysis	Absorption/ Electrodialysis	Absorption/ Calcination	Adsorption/ Desorption
Natural gas*	MJ/kg _{CO2}	-	-	10*	-
Heat	MJ/kg _{CO2}	-	-	-	5.4-7.2
Electricity	MJ/kg _{CO2}	8.2-12.3	6.8	-	0.72-1.08
T (heat)	°C	n. d. a.	n. d. a.	>850°C	95%
CO ₂ purity	-	>99%	>99%	-	>99.5%

* Natural gas is used for heat and electricity supply;
n. d. a.: no data available; CE = Carbon Engineering

Technologies involving electro dialysis has been tested in small lab-scale pilot plants (TRL = 4). The Climeworks technology has been installed in several pilot plants but it is still in an early stage of market introduction (TRL = 6, MRL = 3, CRL = 1).

2.3.4 CO₂ liquefaction and storage

Pure CO₂ is required with very low O₂ content to avoid damage of the catalysts used for methanation and syntheses. The CO₂ can be purified via liquefaction.

Today, CO₂ generally is liquefied if it should be used for other purposes. A typical CO₂ liquefaction plant has been built at an ethanol plant in Lüdinghausen in North Rhine-

Westphalia (NRW) in Germany which is in operation since 2013. The temperature of liquefied CO₂ amounts to about -25°C at an elevated pressure and the purity amounts to 99.999% (vol.) [WIR 2014]. The oxygen content after liquefaction is less than 5 ppm [Buchhauser et al. 2005] which is sufficient for the catalysts used for methanation and synthesis. Table 8 shows the technical and economic data for the CO₂ liquefaction plant in Lüdinghausen.

Table 8: CO₂ liquefaction plant, including storage in Lüdinghausen (NRW)

Parameter	Value
Capacity	2300 kg CO ₂ /h
Production	17,000 t CO ₂ /yr
Electricity consumption	3.5 GWh/a
Storage capacity	300 t (3 tanks, each 100 t)
Investment	3.5 million €

The technology is mature, commercially available, and installed at many CO₂ producing facilities e.g. ethanol plants (TRL = 9, MRL = 6, CRL = 6).

2.4 Methane, methanol, and petrol/diesel produced from renewable electricity (PtX) using hydrogen from electrolysis and CO₂

Synthetic fuels from renewable electricity and CO₂ (power-to-methane, power-to-liquids) have entered fuel discussions over the last few years in Germany, the EU, and internationally (aviation). There are several factors driving synthetic fuels up the energy strategy and environmental policy agendas:

- The re-evaluation of bioenergy for transport with regards to sustainability, availability and costs.
- The vast technical availability potentials of renewable power from wind and solar.
- The drastic decline in power generation costs of PV, onshore and offshore wind.
- The drop-in quality of power-to-methane and power-to-liquids, i.e. the ability to use it without relevant changes in established methane, gasoline, kerosene, diesel or methanol infrastructures and uses.
- Their potential for being strong levers to facilitate the ‘energy transition’ through system & sector integration, e.g. through flexible electrolyser operation for demand-side management as well as the high energy densities of gaseous and liquid fuels for long-term storage and re-electrification.

In the following, the current state of development is described for electricity-based methane, methanol, and gasoline/kerosene/diesel fuels.

2.4.1 Methane via Power-to-CH₄

2.4.1.1 Process description

Hydrogen is generated via water electrolysis and sent to methanation. At the methanation step the following reaction occurs:



The reaction is exothermal. There are two different methanation technologies, the catalytic methanation and the biological fermentation. The biological fermentation can be carried out in a separate bio-reactor or in-situ in the fermenter of a biogas plant.

2.4.1.2 Market readiness level

Several pilot plants have been installed both using catalytic and biological methanation. The technology is in an advanced stage of research and development and is mature leading to a technology readiness level (TRL) of 9. Research and Development issues are compact methanation reactors e.g. plate reactors adequate for fluctuating operation. Since the TRL = 9 the market readiness level (MRL) is 6. The commercial readiness (CRL) level can be set to 3.

2.4.1.3 Estimates of specific financial investments and production costs

As implementation examples of most conversion pathways are still in somewhat early commercial stages, available information on investment and operational cost of existing and planned plants and projects will be quite specific to the respective projects. We will list information on e.g. CAPEX, OPEX, resulting fuel cost or similar economic parameters within the project description for any project where these are available in the literature. It should be noted that economic boundary conditions may differ significantly for larger projects and for future projects based *inter alia* on economies of scale, learning rates, and regulatory changes.

2.4.1.4 Existing and/or projected installations

Almost all power-to-methane plants are installed in the EU. End 2018, 11 power-to-methane plants with a capacity of about 7 MW of CH₄ have been in operation in the EU (Table 9). Further PtCH₄ plants are installed in Switzerland. For some plants the capacity is not known. Therefore, the capacity is slightly higher than shown in Table 9.

Table 9: PtCH₄ capacity in the EU

Unit	In operation	Under construction	Planned	Announced
kW CH ₄ (LHV)	>6818	349	1244	>7960
Nm ³ CH ₄ /h	>685	35	125	>800
Number of plants	13	2	2	2

Including plants under construction, planned, and announced plants the capacity will reach more than 16 MW of CH₄.

In most of the plants the CO₂ is derived from biogas upgrading or CO₂ in biogas streams via direct methanation using the CO₂ fraction of biogas. One plant uses direct air capture (DAC) of CO₂.

Table 10: PtCH₄ plants in the EU

Plant	Location	Status	CO ₂ source	Capacity (kW CH ₄)
Audi e-gas plant Werlte	Germany	In operation	Biogas upgrading	3184
ETOGAS ZSW	Germany	In operation	n. d. a.	124
Eucolino	Germany	In operation	CO ₂ fraction in biogas	53
CoSin	Spain	In operation	n. d. a.	41
P2G Rozenburg	Netherlands	In operation	n. d. a.	2.75
Stromspeicherung Wunsiedel	Germany	Announced	Flue gas	7960
BioPower2Gas Allendorf	Germany	In operation	Biogas upgrading	149
P2G-BioCat	Denmark	In operation	CO ₂ fraction in biogas	1990
DemoSNG	Sweden	In operation	Flue gas	n. d. a.
Jupiter 1000	France	Under construction	n. d. a.	249
EXYTRON demonstration plant	Germany	In operation	Flue gas	10
Power-to-Gas direct methanation Eichhof	Germany	In operation	CO ₂ fraction in biogas	199
Underground Sun Conversion	Austria	Planned	n. d. a.	249
Store&Go-Falkenhagen	Germany	In operation	Bio-ethanol plant	567
Store&Go-Puglia	Italy	Under construction	Air	100
Energiepark Pirmasens	Germany	In operation	CO ₂ fraction in biogas	498
Energiepark Pirmasens (extension)	Germany	In operation	CO ₂ fraction in biogas	996
AFUL Chanterrie - MINERVE	France	In operation	Biogas upgrading	n. d. a.
hybridge	Germany	Announced	n.d.a.	n. d. a.
Total	EU			>16371

n. d. a.: no data available

In chapter A1, some examples are presented.

2.4.1.5 Market expectations

The future requirement of long-term electricity storage for high share of fluctuating renewables in the electricity supply system lead to significant demand of power-to-gas (PtG) plants including PtCH₄ plants.

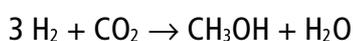
According to [Ausfelder et al. 2017] about 20 TWh of hydrogen (or methane) are required in Germany to bridge two weeks of low solar irradiation and simultaneously low wind speed ('dark calm'). If the equivalent full load period of the PtCH₄ plant is assumed to be 4000 h per year, the installed PtCH₄ capacity would amount to about 5 GW of methane alone in Germany. Extrapolation to the electricity demand of the EU would lead to about 25 GW of methane.

Furthermore, renewable transportation fuel is required to meet the Paris agreement to keep the global temperature increase below 1.5 to 2°C. In [LBST & dena 2017] various explorative scenarios for renewable transportation fuels in the EU to achieve a reduction of greenhouse gas emissions by 95% have been investigated. The final energy demand of road vehicles, rail, aviation, and navigation has been taken into account. For a strongly battery electric vehicle and fuel cell electric vehicle scenario about 520 PJ of methane are required in the EU (besides about 2000 PJ of hydrogen for FCEV, about 2400 PJ of electricity for BEV and trains, and about 5000 PJ of liquid transportation fuels). If the equivalent full load period of the PtCH₄ plant is assumed to be 4000 h per year, the installed PtCH₄ capacity would amount to about 36 GW of methane. In case of a more gaseous transportation fuel involving scenario about 3900 PJ of methane (besides about 1300 PJ of hydrogen for FCEV) are required leading to a required PtCH₄ capacity of about 271 GW of methane.

2.4.2 Methanol via Power-to-Liquid

2.4.2.1 Process description

Hydrogen is converted to methanol via synthesis directly with CO₂ without requirement of reverse water gas shift (RWGS):



The reaction is exothermal. The reaction is carried out at a temperature of 240 to 270°C and a pressure of 8 MPa [Brem 2013], [BIT & Silicon Fire 2013], [Silicon Fire 2013], [Vandal & Bouallou 2013].

2.4.2.2 Market readiness level

The technical readiness level (TRL) of power-to-methanol is 9. As a result, the commercial readiness level (CRL) is at least 3 and the market readiness level (MRL) is 6.

2.4.2.3 Existing and/or projected installations

Until now, there are only a few existing and projected installations in the EU. Another plant is located in Iceland. Most of the existing and projected installations are in the EU.

Table 11: PtCH₃OH plants in the EU, under construction and planned

Plant	Location	Status	CO ₂ source	Capacity (kW CH ₃ OH)
Greenfuel	Germany	In operation	Air	0.91
MefCO ₂ Niederaußen	Germany	Under construction	Flue gas	231
FReSMe	Sweden	Planned	Steel plant	n. d. a.
E2Fuels	Germany	Planned		507
Total	EU			>739

n. d. a.: no data available

In chapter A23.3A2, some examples are presented.

2.4.2.4 Market expectations

The future requirement of long-term electricity storage for high share of fluctuating renewables in the electricity supply system lead to significant demand of power-to-gas (PtG) and/or power-to-liquid (PtL) plants including PtCH₃OH plants.

Methanol can be further processed to gasoline, kerosene, and diesel (see chapter 2.4.3). As a result, power-to-methanol has the same market expectations as the production of petrol and diesel via power to liquid.

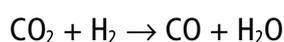
2.4.3 Petrol and diesel via Power-to-Liquid

2.4.3.1 Process description

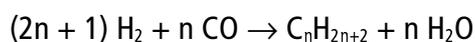
There are two routes for the production of petrol and diesel via power-to-liquid:

- Fischer-Tropsch route
- Methanol route

In case of the Fischer-Tropsch synthesis the CO₂ has to be converted to CO via reverse water gas shift reaction:



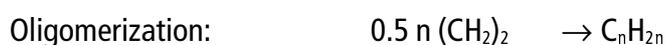
Then the hydrogen is converted to liquid hydrocarbons via the Fischer-Tropsch reaction:



To maximize the share of liquid Fischer-Tropsch products the Fischer-Tropsch reactor is operated in a way to generate a high share long-chain hydrocarbons (waxes). Then the

wax is sent to hydrocracking to generate the desired hydrocarbons naphtha, kerosene, and diesel. Isomerization may be applied to improve the cold flow properties of kerosene and diesel.

In case of the methanol route the hydrogen is converted to methanol with CO₂ (see chapter 2.4.2). The methanol is converted to gasoline via the methanol-to-gasoline (MTG) process or to gasoline and diesel via the methanol-to-olefin-to-gasoline and diesel (MOGD) process. The following reactions occur:



The conversion of methanol to olefins over ZSM-5 catalyst was discovered by Mobil scientists in the 1970ies, together with the similar process of conversion of methanol to gasoline. A MOGD process has been developed subsequently [Avidan 1988]. One of the first large MTG plants has been installed in 1985 in New Zealand to produce gasoline and was operated until 1997 [Helton & Hindman 2014], [Tabak et al. 1986]. Another MTG plants have been built in 2009 in the Shanxi Province in China with a capacity of 2500 barrel of gasoline per day (~300 t/d) and in 2011 with a capacity of 25,000 barrel of gasoline per day (~3000 t/d) [Helton & Hindman 2014]. The MTG and the MOGD process can be considered as mature (TRL = 9) and commercially available (MRL = 6).

Today, the MTG process is provided by ExxonMobile and Haldor Topsoe (TIGAS: Topsoe Improved Gasoline Synthesis). Air Liquide provides a methanol-to-olefin process for the production of propylene (methanol-to-propylene - MTP) which is an intermediate step to produced gasoline, kerosene, and diesel. Air Liquide builds MTG plants using ExxonMobile technology.

2.4.3.2 Market readiness level

The technical readiness level (TRL) of power-to-liquid via the Fischer-Tropsch route including reverse water gas shift (RWGS) but without CO₂ supply is 9. As a result, the commercial readiness level (CRL) is at least 3 and the market readiness level (MRL) is 6.

2.4.3.3 Existing and/or projected installations

End 2019, there were two plants in operation in the EU. The Sunfire PtL plant in Dresden meanwhile is out of operation. However, there are 2 plants announced. Furthermore, there are planned and announced plants in Switzerland, Norway, and Canada.

Table 12: Power-to-liquid plants for the production of petrol, kerosene, and diesel in the world

Plant	Location	Status	CO ₂ source	Capacity (kW fuel)
Audi PtL	Switzerland	Announced	Biomass plant	435
GreenPower2Jet (GP2J)	Germany	Announced	n. d. a.	n. d. a.
KEROSyN100	Germany	Announced	n. d. a.	n. d. a.
Nordic Blue Crude	Norway	Planned	n. d. a.	11,162
Powerfuel	Germany	In operation	n. d. a.	119
SOLETAIR	Finland	In operation	Air	29
Sundance Clean Methanol/ Blue Fuel Energy	Canada	Announced	Flue gas	947,640*

n. d. a.: no data available; *Mainly from natural gas, partly from renewable electricity

The Sundance Clean Methanol plant in Canada will only partly use hydrogen from water electrolysis (from a 20 MW_e PEM electrolysis plant). The whole plant will consist of water electrolysis, autothermal reforming (ATR) of natural gas, methanol synthesis, and methanol-to-gasoline (MTG) process. The water electrolysis generates hydrogen which is added to the syngas generated by the ATR plant and supplies oxygen for a steam power plant with a natural gas fuelled oxy burner. The waste heat is used for greenhouses.

Very lately, several large-scale plants in the multi-megawatt scale have been announced, especially in Germany in the context of the "Reallabor" funding framework.

In chapter A3, some examples are presented.

2.4.3.4 Market expectations

Renewable transportation fuel is required to meet the Paris agreement to keep the global temperature increase below 1.5 to 2°C. In [LBST & dena 2017] various explorative scenarios for renewable transportation fuels in the EU to achieve a reduction of greenhouse gas emissions by 95% have been investigated. The final energy demand of road vehicles, rail, aviation, and navigation has been taken into account. Even for a strongly battery electric vehicle and fuel cell electric vehicle scenario about 5000 PJ of liquid transportation fuels are required in the EU in 2050 (besides about 2000 PJ of hydrogen for FCEV, about 2400 PJ of electricity for BEV and trains, and about 520 PJ of methane). If the equivalent full load period of the power-to-liquid (PtL) plant is assumed to be 4000 h per year, about 347 GW of PtL capacity has to be installed.

2.5 Methane, methanol, and petrol/diesel produced using hydrogen from artificial photosynthesis

2.5.1 State of research of artificial photosynthesis

A circle of national academies of science in Germany (Acatech, Leopoldina, Union) have recently published a report on the state of research, scientific-technological challenges, and perspectives of artificial photosynthesis [acatech et al. 2018].

With regards to the **state of research** on artificial photosynthesis, the authors of [acatech et al. 2018, p 5] come to the conclusion that while the

« scientific basis for artificial photosynthesis has been thoroughly investigated over the last two decades [and while] highly promising test systems have already been developed in German and international projects which have primarily investigated and optimised sub-reactions of the overall processes [and while] the first relatively large power-to-X plants have already begun test operation, artificial photosynthesis [as a completely integrated, direct reaction system] in contrast still largely remains at the level of basic research ».

The authors consider that "suitable [direct reaction] systems are so far still at the laboratory prototype stage which means that a reliable cost-benefit analysis and an economically justifiable outlook for the future are as yet not possible."

Regarding the **main hurdles** for the further development of direct reaction artificial photosynthesis, the authors refer to industry experts that see "scalability of the existing approaches as being the essential challenge." [acatech et al. 2018, p 5]

Furthermore, it is far from being self-evident why direct reaction systems have to have a better techno-economic performance compared to individual specialized processes in a production plant or compared to those that can be arranged to build value chains of intermediate products with possibly several downstream value chains (such as the concept of petro-chemical plants or bio-refineries). Separate processes allow for fit-for-purpose scaling of individual processes in optimal operating conditions and intermediate products to be used for different purposes. Systems fully integrated with the aim of direct conversion regularly have to deal with challenges like reactor design trade-offs, inhibition reactions and overall lower reaction kinetics resulting in sub-optimum design and performance. Another example (see the following chapter) is dispersed gas generation resulting in an integrated artificial photosynthesis process leading to higher efforts for product gas collection as opposed to dispersed electricity generation, electricity collection, which is then followed by a concentrated gas production in an integrated power-to-x plant.

2.5.2 Example pathways for (direct reaction) artificial photosynthesis

These technologies are at an early stage of research and development.

In the following, examples for recent technology developments in the field of artificial photosynthesis are given.

a) Photo-catalysis (photo-electrochemical cells – PEC)

The conventional way of producing hydrogen from solar energy comprises two single process steps. First, electricity is generated via photovoltaic cells. Secondly, the electricity drives an electrolyser which splits water into oxygen and hydrogen.

Photo-electrochemical cells (PEC) combine photovoltaic electricity generation and electrolysis in a single process. A photo-electrochemical cell has similarities to a photovoltaic cell (PV). Basically, a PV-cell separates electrons and holes in the semiconductor material. The electric current via external loads recycles the electrons. The PEC-device separates anode and cathode via an electrolyte in between them. It consumes the free electrons at the solar irradiated cathode by the formation of neutral hydrogen molecules from positive protons (H^+), which are attracted by the cathode during the water splitting process. Negative oxygen ions (usually bound in negatively charged OH^- ions) are attracted by the anode where they are transformed in neutral oxygen molecules by stripping off their surplus electrons at the anode. A current recycles the electrons back to the anode. The major difference of PV-cells and PEC-devices is that anode and cathode are separated by an electrolyte.

Basically, four different technological realisations have been investigated in the literature:

- Type I: Nanoparticles consisting of hematite (Fe_2O_3) and thin catalyst layers which are mixed in a single compartment with colloidal suspension. The whole cell is encapsulated while the mixed oxygen/hydrogen gas is removed and collected through a pipe (dispersed gas handling).
- Type II: Nanoparticles consisting of hematite (Fe_2O_3) and thin catalyst layers which are mixed in a dual compartment with colloidal suspension. The compartments are doubled, alternating rows collecting hydrogen and oxygen, respectively.
- Type III: Planar PEC-array, as explained above.
- Type IV: Planar high efficiency PEC arrays which are irradiated by concentrated solar light (enhancement by a factor of 10 or more).

Each of these types has its advantages and disadvantages, which are shortly explained below.

Figure 5 depicts a Type III as an example, where the anode is irradiated. Type IV reactors are similar with the difference that the incoming solar radiation is concentrated to higher power density requiring high power anode materials (e.g. GaAs-compounds). The

absorbed energy shifts the valence electrons into the conduction band leaving holes in the valence band. These holes are neutralised with electrons from the decomposition of the negative OH⁻-radicals into oxygen molecules and water. The surplus electrons in the conduction band move to the cathode. At the cathode, water molecules are dissociated into hydrogen molecules and OH⁻-radicals by consuming the electrons which are supplied by the electric current once anode and cathode are connected. The OH⁻-radicals move through the electrolyte to the anode where they are decomposed as already explained.

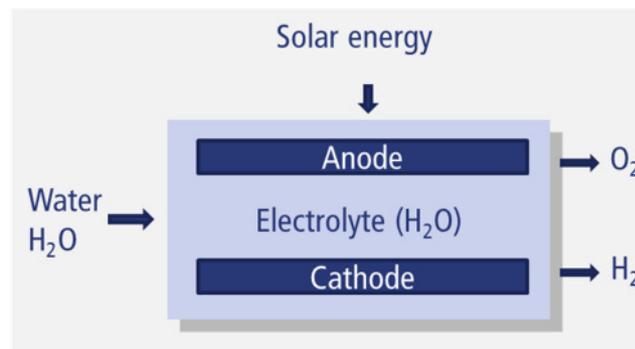


Figure 5: Schematic view of a Type III (planar) photo-electrochemical device for hydrogen production from solar energy (graphic: LBST)

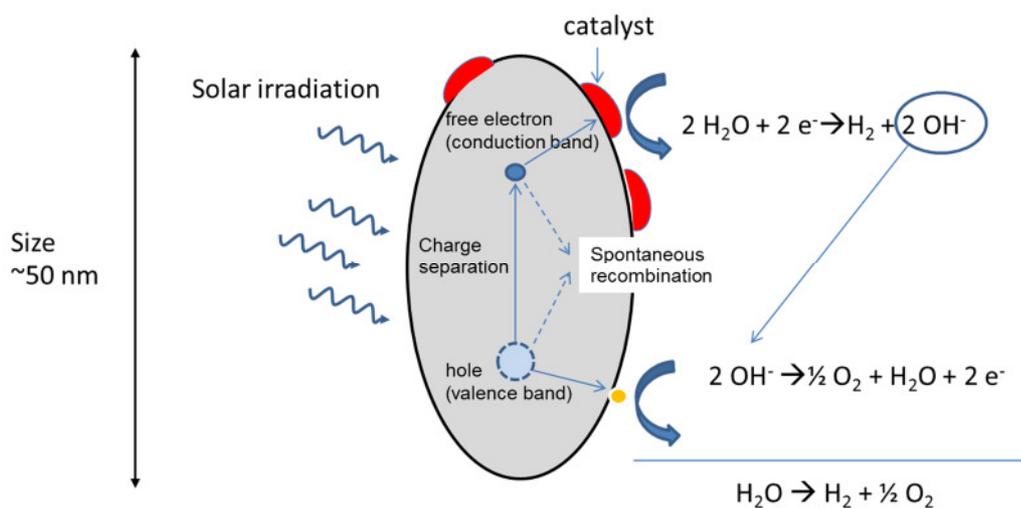


Figure 6: Schematic view of a Type I or Type II nanoparticulate photo-electrochemical device for hydrogen production from solar energy. The nanoparticulates are suspended in the electrolyte (graphic: LBST)

Inputs to the process are:

- Solar photons which provide the required energy
- Water (electrolyte) serving as “fuel” for the hydrogen production.

PECs are currently at a low stage of research and development with TRL 2 to 5.

Some PECs use nanoparticles (type I, II), while others require rare elements (type III, IV).

Actors in the field

- Delft University of Technology, The Netherlands, <http://www.tudelft.nl/en/current/latest-news/article/detail/tu-delft-verbetert-productie-vanwaterstof-uit-zonlicht/> (Roel Van de Krol)
- Department of Chemical System Engineering, School of Engineering, The University of Tokyo, Tokyo, Japan
- EPFL Lausanne, Micheal Graetzel, Switzerland
- Fritz-Haber-Institute of the Max-Planck-Society, Theory Department, Berlin, Germany
- Hawaii Natural Energy Institute, School of Ocean and Earth Science and Technology University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA (E. Miller, R. Rocheleau), see <http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/30535x.pdf> (Miller 2001)
- Helmholtz Zentrum Berlin, Germany, http://www.helmholtz-berlin.de/pubbin/news_seite?nid=13764&sprache=de&typoid=1 (van de Krol)
- Helmholtz-Gesellschaft (Prof. J. de Kol)
- Max-Planck Institute of Colloids and Interfaces, Department of Colloid Chemistry, Research Campus Golm, Postdam, Germany
- National Renewable Energy Laboratory (NREL), USA, <http://techportal.eere.energy.gov/technology.do/techID=1076>
- Research Institute of Photocatalysis, State Key Laboratory Breeding Base of Photocatalysis, Fuzhou University, Fuzhou, China
- University of Stuttgart, Institute for Materials Science (Prof. Dr. Anke Weidenkaff)

b) SoCalGas/Opus12 PEMEL direct methanation – Berkeley (California), USA

Status: Ongoing

Participants: Southern California Gas Co. (SoCalGas), Opus 12

Characteristics: Power-to-methane (PEM single conversion)

Description: Southern California Gas Co. (SoCalGas) and Opus 12 today announced the successful demonstration of a new process to convert the carbon dioxide in raw biogas to

methane in a single electrochemical step. Opus 12, a clean-energy startup incubated in the Cyclotron Road program at Lawrence Berkeley National Lab, used a new type of Polymer Electrolyte Membrane (PEM) electrolyser to convert carbon dioxide to methane.

The nine-month study was funded by SoCalGas along with two start-up-funding organizations, the Rocket Fund of Caltech's FLOW program and Elemental Excelsior.

This feasibility study was the first phase of research that will also explore new catalysts, modifying the catalyst layer formulation, and other ways to enhance the system's methane conversion performance.

Source: <https://www.sempra.com/newsroom/press-releases/socalgas-and-opus-12-successfully-demonstrate-technology-simplifies>

Opus 12, a US-based clean-energy startup incubated in the Cyclotron Road program at Lawrence Berkeley National Laboratory, California, used a new type of Polymer Electrolyte Membrane (PEM) electrolyzer to convert carbon dioxide (CO₂) to methane (CH₄), showing that instead of wasting the CO₂ in raw biogas, it can be converted to methane using renewable electricity.

Source: <https://bioenergyinternational.com/biogas/socalgas-opus-12-successfully-demonstrate-power-gas-technology>

Homepage: <https://www.sempra.com/newsroom/press-releases/socalgas-and-opus-12-successfully-demonstrate-technology-simplifies>

2.6 Ethanol from microbial fermentation of industrial off-gases by bacteria

2.6.1 Process description

Syngas consisting of CO₂, CO and H₂ is converted to ethanol via fermentation. The process is capable to use a wide range of syngas composition. Even pure CO can be used as feedstock. According to [Phillips et al. 2017] the following reactions can occur:



The synthesis gas can be derived from gasification of biomass and municipal solid waste, from industrial waste gases, and from water electrolysis where the CO₂ is separated from air.

2.6.2 Market readiness level

A pilot plant has been built in New Zealand in 2008. Pre-commercial plants have been built at Baosteel in China in 2012, at Capital Steel in China in 2013, and at WBT in Taiwan in 2014. A commercial plant had been built in Shougang in China in 2018. Further commercial plants are under construction at AcelorMittal in Belgium, at Indian Oil in India, at Aemetis in the USA, and in Swayana in South Africa [LanzaTech 2018].

The TRL is 9. As a result, the commercial readiness level (CRL) is at least 3 and the market readiness level (MRL) is 6.

2.6.3 Existing and/or projected installations

Participants: LanzaTech, Chicago, Illinois, USA

Characteristics: Biological conversion of gas mixtures consisting of H₂, CO, and CO₂ to ethanol (gas fermentation).

Description: LanzaTech uses a genetically modified *C. autoethanogenum* strain to convert gas mixtures consisting of CO₂, CO and H₂ into ethanol [Anggraini et al. 2018]. The LanzaTech process consists of gas reception, syngas compression, fermentation to ethanol, and product recovery.

Table 13 shows pilot and pre-commercial plants based on the LanzaTech process.

Table 13: Pilot and pre-commercial plants based on the LanzaTech process

	Unit	Blue Scope	BaoSteel	Shougang
Region	-	New Zealand	China	China
Status	-	Operation	Operation	Operation
Begin of operation	-	2008	2012	2013
Capacity (ethanol)	gal/yr	15,000	100,000	100,000
	l/yr	56,775	378,500	378,500
	l/h	6.48	43.21	43.21
	kg/h	5.15	34.31	34.31
	kW _{ethanol}	38.3	255.4	255.4

Table 14 shows commercial plants based on the LanzaTech process.

The LanzaTech plant at AcelorMittal in Ghent in Belgium has a capacity of about 21 million gal per year or about 80 million l of ethanol per year [AcelorMittal 2018], [CNBC 2018]. The project involves a combined investment package of over €100 million from ArcelorMittal, EU Horizon 2020 and the European Investment Bank, and will start to

yield results in 2019 [AcelorMittal 2018]. In [LanzaTech 2018] the plant at AcelorMittal is called 'commercial' plant. In [AcelorMittal 2018] the plant is called 'demonstration' project.

The ethanol production capacity of the LanzaTech plant at Indian oil will amount to about 11 million gal per year, that of the plant at Aemetis will amount to about 12 million gal per year, that of the plant at Shougang will amount to about 16 million gal per year, and that of the plant at Swayana will amounts to about 17 million gal per year [CNBC 2018].

Table 14: Commercial plants based on the LanzaTech process under construction

	Unit	Shougang	ArcelorMittal	Indian Oil	Aemetis	Swayana
Region	-	China	Belgium	India	USA	South Africa
Begin of operation	-	2018	2019	2019	2020	2020
Gas source	-	Steel mill	Steel mill	Refinery	Biomass gasification	Ferroalloy and titania smelting
Capacity (ethanol)	gal/yr	16,000,000	21,000,000	11,000,000	12,000,000	17,000,000
	m ³ /yr	60,560	79,485	41,635	45,420	64,345
	m ³ /h	6.9	9.1	4.8	5.2	7.3
	t/h	5.5	7.2	3.8	4.1	5.8
	MW _{ethanol}	40.9	53.6	28.1	30.6	43.4
Investment	M€	n. d. a.	100	n. d. a.	n. d. a.	n. d. a.

n. d. a.: no data available

2.6.4 Market expectations

LanzaTech focus on waste gases from steel production plants. However, if blast furnaces are replaced by direct reduction processes, less CO rich waste gases will be available. The advantage of direct reduction of iron ore is that hydrogen generated via water electrolysis with electricity from renewable energy sources can be used. A pilot plant for the production of steel via direct reduction of iron ore using renewable hydrogen is planned in Luleå in Norrbotten iron ore fields in Sweden [HYBRIT 2017].

On the other hand, the LanzaTech process also can convert mixtures of CO₂ and H₂ generated by water electrolysis to ethanol leading to market expectations similar to other power-to-liquid technologies (see chapter 2.4.2 and chapter 2.4.3).

2.7 Ethanol from microbial fermentation of syngas from sewage gases and natural gas by bacteria

One way of thermo-catalytic reforming is followed by EU research project '2synfuel' (2017-2021, <http://www.tosynfuel.eu>), with products H₂-rich synthesis gas, biochar, and liquid bio-oil.

Another way is the plasma-supported conversion of waste streams as e.g. pursued by US technology provider InEnTec from Richland/WA (<http://www.inentec.com>).

The biological fermentation of syngas to ethanol follows the same lines as described in chapter 2.6 for using industrial off-gases.

The overall pathway is depicted in Figure 7.

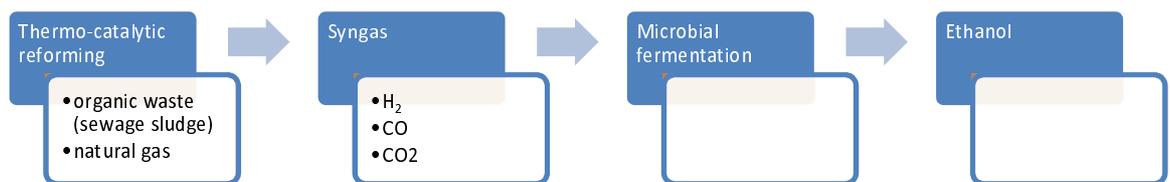


Figure 7: Pathway for ethanol production via fermentation of syngas from thermos-catalytic reformation of gas from fossil and biogenic origin

3 INCENTIVES AND SUPPORT POLICIES TO TECHNOLOGY INVESTMENT AND DEPLOYMENT

The greenhouse gas emission reduction goals agreed at the Paris climate conference (COP21) in December 2015 are the overarching drivers towards the introduction of low and zero emission advanced alternative fuels into the transport sector. Transport is one of the most significant contributors to these emissions but has shown the least progress of all emitting sectors in the past years. However, at present, corresponding incentives and support policies in most cases do not directly address advanced alternative fuels but rather provide a general framework for reducing sector emissions.

In this section, we review prominent support mechanisms or incentives aiming at promoting advanced alternative fuels, both in the EU and globally. Where barriers to future technology development and market uptake are apparent, we comment on potential actions or policy instruments to overcome these.

3.1 European Union policy

In general, the European Commission addresses the following main areas of action in the transition to a future-oriented, environmentally friendly transport and mobility sector (see e.g. COM(2016) 501 Final)

- Higher efficiency of the transport system
- Low-emission alternative energies for transport
- Low- and zero-emissions vehicles

While the Europe on the Move package (COM/2017/0283 final) addresses the general boundary conditions for the future of mobility in the EU, including considerations on the transport and refuelling infrastructure, the above areas of action are addressed with specific measures and goals in the following European policies.

- The recast of the Renewable Energy Directive (EU) 2018/2001 (RED II), essentially replacing the former Renewable Energy Directive from 2009 and also extending the current Fuel Quality Directive beyond 2020, targets a share of renewable energy within the final consumption of energy in the transport sector of at least 14% by 2030. In the RED II, the electrofuels addressed in this report are included in the so-called “renewable liquid and gaseous transport fuels of non-biological origin”, as their energy content is derived from renewable sources other than biomass. Their renewable nature depends on the source of the electricity used for their production and Article 27 of the RED II outlines how this is to be taken into account. The waste-stream based fuels considered here are covered by the “recycled carbon fuels” category of the RED II. Both renewable liquid and gaseous transport fuels of non-biological origin and recycled carbon fuels are explicitly

covered in their contribution towards the renewable energy goals of the transport sector. However, while renewable liquid and gaseous transport fuels of non-biological origin shall be taken into account by Member States in calculating the renewable energy share in transport, this is only optional for recycled carbon fuels (see RED II Articles 25 and 27).

- Other European regulations limit GHG emission for new cars and vans including (EC) No 443/2009 and (EU) No 510/2011; tighter emission limits post 2020 have been discussed and are being implemented. However, these mainly address vehicle efficiency and, while hydrogen fuel cell electric vehicles are incentivised, the use of advanced alternative fuels in combustion engines generally does not count towards the respective emission goals. The discussed proposals for new lower emission standards do not include provisions for the use of advanced alternative fuels either, even though the automotive industry has been advocating it.
- The Clean Vehicles Directive 2009/33/EC requires that energy and environmental impacts linked to the operation of vehicles over their whole lifetime are taken into account in public purchase decisions. As in the above directives, the Clean Vehicles Directive mainly targets vehicle efficiency and is not specific to fuels. The same holds for the Energy Efficiency Directive 2012/27/EU. However, a currently discussed revision of the Clean Vehicles Directive also counts vehicles using alternative fuels as defined in the Alternative Fuels Infrastructure Directive 2014/94/EU as 'clean vehicles'; such fuels include inter alia hydrogen and synthetic fuels.

3.2 Rest of the world

While electrofuel production is seeing prototype deployment in Europe, activities outside of Europe are still in their infancy (see task 1). As a result, there are no relevant policies supporting advanced alternative fuels as covered in this report outside of Europe.

China is mainly promoting electric mobility for road transport under the scheme for so-called New Energy Vehicles. After a recent policy change, subsidies for battery electric vehicles have been reduced but remain high for fuel cell electric vehicles.

In the USA, an important policy for the promotion of alternative fuels is the national Renewable Fuel Standard (RFS) programme, which aims to increase the volume of renewable fuel that is blended into transportation fuels. The programme focuses strongly on biofuels. So far, advanced alternative fuels as covered in this report are not yet covered by the RFS programme.



3.3 Outlook and barriers

Alternative fuels with a low TRL will generally be able to benefit from European as well as national research and development grants. However, eventually, advanced alternative fuels will be competing with other low or zero emission options in transport on availability and cost on a total cost of ownership basis. The cost of electrofuels is mainly driven by the underlying cost of electricity. In all European countries, various taxes and levies constitute a significant share of the electricity price. As a result, the question of which of these taxes and levies apply in what way when using renewable electricity to produce electrofuels is a decisive factor for the cost and resulting competitiveness of an advanced fuel.



ANNEX

A1 METHANE VIA POWER-TO-CH₄

A1.1 AFUL Chantrerie – MINERVE – Nantes, France

Status: In operation since February 2018

Participants: ADEME, Departmental Council 44, ENGIE-Cofely, FEDER, GRDF, GRTGaz, IMT Atlantic, Nantes Métropole, Polytech Nantes, Pays de la Loire Region, SYDELA, SyDEV

Characteristics: 12 kW_e electrolyzer, methanation

Description: Supported by ADEME, Europe and the Pays de la Loire region, Minerve aims to store renewable energy as a gas. Placed on the building of a biomass boiler, the demonstrator consists of a 12 kW_e electrolyser producing hydrogen which, in reaction with CO₂ in a methanation reactor, produces synthetic methane (CH₄). The gas produced is then used as fuel for CNG vehicles. If necessary, the hydrogen can also feed directly to the boilers of gas boiler. The project was set up on the site of the Chantrerie in Nantes by the AFUL (Association Foncière Urbaine Libre), a consortium bringing together industrialists and schools. The overall amount of the transaction amounts to € 1,560,000.

A1.2 Agricultural Centre at the Eichhof – Bad Hersfeld, Germany

Status: In operation since January 2012.

Participants: Fraunhofer IWES, ZSW, ETOGAS (today: Hitachi Zosen INOVA Etogas)

Characteristics: 25 kW electrolyser, methanation.

Description: In periods of excess electricity, hydrogen will be produced for subsequent methanation with CO₂ from a biogas plant. In Bad Hersfeld (Germany), CO₂ is not extracted from the biogas stream. Instead, the biogas stream including CO₂ is fed into the methanation plant ('direct methanation'). Separate CO₂ extraction in a biogas upgrading facility is not required. Methanation of the CO₂ increases the methane content of the gas stream to over 90%. If the gas is stored locally (e.g. in storage balloons) and elaborate, cost-intensive conversion measures are not required, this process may be suitable for smaller biogas plant from 250 kW_e (equal to about 750 kW methane) [IWES 2012], [IWES 2013], [Etogas 1/2013]. Methane thus produced is reconverted to electricity like biogas. The output is 6 Nm³/h H₂ or 1.5 Nm³/h of methane, respectively [DVGW 2013].

A1.3 AUDI Werlte – Werlte, Germany

Status: In operation since June 2013.

Participants: AUDI AG, ETOGAS (today: Hitachi Zosen INOVA Etogas), EWE AG, MT BioMethan GmbH, ZSW, IWES

Characteristics: Alkaline electrolysis, methanation, CO₂ from biogas, methane feed-in into the natural gas grid.

Description: The facility consisting of alkaline electrolysis and methanation produces about 320 Nm³/h of synthetic methane (CH₄). The CO₂ is supplied by a biogas plant. The CO₂ extraction from biogas is carried out via scrubbing with mono-ethanolamine (MEA). Re-generation of the scrubbing agent is carried out applying heat from the exothermic methanation process. The electrical power consumption amounts to about 6300 kW including all auxiliary power units (e.g. rectifier, pumps, fans, controls). In consequence, the total energy conversion efficiency is 51%. The 350 Nm³ product gas per hour reported in [Schoeber 2013] are likely to include impurities. Under the assumption that the reported 350 Nm³ refer to purified methane, the total energy conversion efficiency improves to 55%. This result is close to the 54% cited by AUDI. [Rieke 2013] reports an electricity consumption of 27,600 MWh for the production of 1000 t of methane (13,890 MWh in reference to the lower heating value). In consequence, the energy conversion efficiency is about 50%.

The plant has been in operation since June 2013.

A1.4 CO₂RRECT – Niederaußem, Germany

Status: The plant has been operated between February and December 2013 (duration of the project).

Participants: Bayer Technology Services BTS, RWE Power, Siemens, Bayer Material Science BMS, et al.

Characteristics: 300 kW electrolyser, methanation, CO₂ from flue gas from a lignite-fired power plant

Description: The plant consists of a 300 kW electrolysis plant, methanation, and CO₂ extraction from flue gas from a lignite-fired power plant.

The abbreviation CO₂RRECT stands for CO₂ Reaction using Renewable Energies and Catalytic Technologies. In this research facility at RWE Power, a number of different catalysts for methanation are tested. The electrolyser was manufactured by Siemens and is tested for flexibility. The production of methanol is tested as well. The hydrogen output amounts to 50 Nm³/h.



Figure 8: Electrolyser at power plant Niederaußem, Germany (Source: RWE)

The plant has been in operation since February 2013.

A1.5 Compact biogas plant 'EUColino' with in-situ methanation – Schwandorf, Germany

Status: In operation since November 2012.

Participants: MicrobEnergy GmbH (affiliate of Viessmann)

Characteristics: 108 kW, methanation.

Description: The plant produces 21 Nm³/h of hydrogen or 5 Nm³/h of synthetic methane. Biogas is used as a CO₂ source. In contrast to catalytic methanation (e.g. the project in Werlte), here methanation is achieved biologically with microorganisms in-situ in the fermenter of the biogas plant. Thus, the methane content of the biogas stream at the exit of the fermenter is increased. The synthetic methane is used for electricity production along with biogas.



Figure 9: Compact biogas plant 'EUColino' in Schwandorf (Source: MicrobEnergy GmbH)

A1.6 ETOGAS ZSW pilot plant – Stuttgart, Germany

Status: In operation since October 2012.

Participants: ZSW, IWES, ETOGAS (today: Hitachi Zosen INOVA Etogas), Hydrogenics

Characteristics: 250 kW entire plant, methanation, methane feed-in into the natural gas grid.

Description: At the ZSW, PtG plants with different configurations have been tested for a number of years. An alkaline pressure electrolyser was used in the past. The novel system works with an alkaline electrolyser, model HySTAT 60 by Hydrogenics, and produces 60 Nm³ of hydrogen per hour fed into a subsequent methanation with a maximum output of 15 Nm³ of methane per hour. Daily methane production is reported to come to 300 Nm³, or an average of 12.5 Nm³ per hour. According to the manufacturer the electricity consumption of the electrolyser amounts to 5.2 kWh/Nm³ hydrogen. The electrical power consumption at full electrolyser load would thus amount to 312 kW.

[Etogas 2/2013] reports a maximum electrical power consumption of 280 kW direct current (DC) with a hydrogen output of 65 Nm³ hydrogen per hour (including the rectifier, the electrical power consumption would be higher).

[ZSW 2012] reports an electrical power consumption of 295 kW DC given an output of 65 Nm³ hydrogen per hour. This hydrogen is converted into 15 Nm³ of methane per hour in the subsequent methanation plant. Both [Etogas 2/2013] and [ZSW 2012] report their data assuming a current density of 430 mA/cm², i.e. equal load on the electrolyser. Assuming an energy conversion efficiency of 95% for the rectifier, the resulting electrical power consumption approximately amounts to 311 kW. This is consistent with the 312 kW reported above from the technical data published by Hydrogenics. The combination of an electrical power consumption of 312 kW and a methane output of 15 Nm³/h result in an energy conversion efficiency of about 48%.

The output of 12.5 Nm³ CH₄ per hour are probably achieved with a low electrolyser load. The total energy conversion efficiency amounts to about 50% based on an electrical power consumption of 250 kW and a methane output of 12.5 Nm³/h. In all likelihood, the reported 250 kW_e refer to the electrical power consumption after the rectifier (DC) and not at full electrolyser load.

Waste heat is utilised within the institute. In August 2013, the produced gas reached natural gas standards (high methane content).



Figure 10: PtG plant at the ZSW in Stuttgart, Germany (Source: ZSW Stuttgart)

A1.7 Jupiter 1000 – Fos-sur-Mer, Bouches-du-Rhône, France

Status: Under construction, start-up 2019

Participants: GRTgaz (coordinator), ATMOSTAT (methanation reactor), CEA (R&D methanation reactor), CNR, Leroux & Lotz Technologies (CO₂ capture plant), Le Port de Marseille Fos, McPhy (electrolyser), RTE, TIGF (Transport et Infrastructures Gas France)

Characteristics: Water electrolysis (alkaline and PEM), methanation, CO₂ capture from flue gas, CO₂ compression and storage

Description: 500 kW_e alkaline electrolysis capacity and 500 kW_e PEM electrolysis capacity are installed (Manufacturer: McPhy). The hydrogen production capacity amounts to 200 Nm³ per hour. A part of the hydrogen is sent to methanation. The capacity of the methanation plant amounts to 25 Nm³ of CH₄ per hour. A mixture of hydrogen and CH₄ is injected into the natural gas grid. Jupiter 1000 is co-financed by the European Union under the ERDF funds (regional developments), by the government as part of the 'Investissements d'Avenir' program entrusted to ADEME and the Provence-Alpes-Côtes d'Azur regional council.

Homepage: <https://www.jupiter1000.eu>

A1.8 Store&Go-Falkenhagen – Falkenhagen, Germany

Status: In operation since May 2018

Participants: 27 partners from six European states. The plant will be built and operated by Uniper in collaboration with Thyssenkrupp Industrial Solutions, the Deutscher Verein des Gas- und Wasserfaches (DVGW), and the Karlsruhe Institute of Technology (KIT).

Characteristics: alkaline water electrolysis, catalytic methanation, direct air capture of CO₂

Description: The electrolysis plant has been supplied by Hydrogenics and has a capacity of about 2000 kW_e generating 360 Nm³ of H₂ per hour which is not fully used for methanation. The electrolysis plant consists of 6 units, 60 Nm³ H₂/h each. The capacity of the methanation plant is 57 m³ of CH₄ per hour. The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691797.

Homepage: <https://www.storeandgo.info/demonstration-sites/germany>

A1.9 Store&Go-Puglia – Troia (Puglia), Italy

Status: Under construction

Participants: 27 partners from six European states

Characteristics: alkaline water electrolysis, catalytic methanation, direct air capture of CO₂, CH₄ liquefaction

Description: The plant will exploit hydrogen produced by the electrolyser inherited from the INGRID Project ID 24 (Hydrogenics, 4 units, total 1152 kW_e, 240 Nm³ H₂/h). For the project electrolysers with a capacity of 200 kW_e will be used to produce 7.2 kg of liquefied methane per hour (100 kW CH₄ based on the LHV). The direct air capture (DAC) plant for CO₂ supply is supplied by the Swiss company Climeworks. The total electricity input including CO₂ supply and CH₄ liquefaction amounts to 246.1 kW leading to an efficiency of 45.7% based on the LHV.

Homepage: <https://www.storeandgo.info/demonstration-sites/italy>

A1.10 Viessmann research facility – Allendorf, Germany (with in-situ methanation)

Status: The plant has been operated between September 2013 and August 2016 (duration of the project).

Participants: Viessmann



Characteristics: Biogas plant with associated PtG plant.

Description: In August 2013, Viessmann opened a new biogas plant at the company head-quarters in Allendorf, Germany. The biogas plant has been extended by a PtG plant. Hydrogen produced with an electrolyser is methanated with the CO₂ fraction in the biogas stream and fed into the natural gas grid. Methanation is carried out biologically in situ in the fermenter of the bio-gas plant, similar to the MicrobEnergy plant in Schwandorf, Germany.

A1.11 SoCalGas/NREL P2G+biomethanation demo – Golden (Colorado), USA

Status: in operation

Participants: National Renewable Energy Laboratory (NREL), Southern California Gas Company (SoCalGas), Proton/Nel, Electrochaea

Characteristics: Power-to-H₂ with subsequent biological methanation

Description: Demonstration of the first U.S. power-to-gas system for energy storage at the NREL Energy Systems Integration Facility (ESIF). The demonstration consists of the following pathway elements: Renewable power → Low-temperature water electrolyser (Proton Onsite M series electrolyser, Proton is a Nel company) → Biological methanation (700 L 18 bar bioreactor containing archaea microorganisms provided by Electrochaea) → Feed-into methane gas infrastructure.

Sources:

- <https://www.protononsite.com/news-events/nel-proton-proud-have-provided-m-series-pem-electrolyzer-stack-supplying-hydrogen-first>
- <https://www.nrel.gov/docs/fy19osti/73025.pdf>

The hydrogen system at the ESIF stores more than 300 kg of gas at pressures up to 12,700 psig.

Source: <https://www.nrel.gov/news/features/2017/undersea-microbes-provide-path-to-energy-storage.html>

Objective: Power-to-gas performance characterisation to indicate the commercial viability of the biological methanation approach relative to other energy storage technologies and to provide insights into MW-scale system designs. The research team will combine these insights with renewable energy resource data to identify optimal locations in California and the western half of the U.S. power grid where this grid-scale energy storage system would be most economical.

Source: <https://www.nrel.gov/docs/fy18osti/68939.pdf>

Exploitation: This project will allow for:

- Improvements in the next-generation reactor design, currently conceived as being 10-50 megawatts in capacity for large-scale, long-term energy storage systems
- Large-scale hydrogen production, which can serve as a feedstock for a variety of chemical and energy needs, including transportation in hydrogen-powered fuel cell vehicles, ammonia production, and synthetic fuel production
- Informing policy makers who may want to enable or incentivize the deployment and expansion of this large-scale energy storage system for utility grids

Source: <https://www.nrel.gov/docs/fy18osti/68939.pdf>

Homepage: <https://www.socalgas.com/smart-energy/renewable-gas/power-to-gas>

A1.12 hybride – Lingen (Lower Saxony), Germany

Status: Announced as per February 2019

Participants: Amprion (electricity transmission grid operator), Open Grid Europe (OGE, gas transmission grid operator)

Characteristics: power-to-gas (PtG) project comprising power-to-hydrogen (PtH₂) and parts thereof to be synthesized to methane (PtCH₄)

Description: Amprion and Open Grid Europe (OGE) are planning to build a 100MW electrolysis plant along with hydrogen infrastructure in the district of Emsland in Lower Saxony in Germany. The project dubbed "hybride" has progressed to a stage where the planning approval process can start. Electricity from renewable sources shall be converted into green hydrogen and partly into green methane. The project partners intend to also convert an existing OGE pipeline into a dedicated hydrogen pipeline. The partners expect project costs to be around € 150 million. In the medium to long term, the natural gas storage facilities in this the region can also be used for hydrogen storage. In the future, further parts of the gas infrastructure is planned to be converted to allow transportation of hydrogen to the Ruhr area and beyond. Small quantities of hydrogen can also directly be injected into the natural gas grid or the hydrogen to be converted into methane, which could then be fed into the natural gas pipeline system without any restrictions.

The project realisation is subject to the development of an adequate regulatory framework that would allow for improving the project economics in the field.

Source: <https://ptg.amprion.net/Dokumente/Pressemitteilungen/110219-PM-Hybride-final-EN.pdf>

Homepage: www.hybride.net

A2 METHANOL VIA POWER-TO-LIQUID

A2.1 George Olah Renewable Methanol Plant – Svartsengi, Iceland

Status: In operation since 2012

Participants: Carbon Recycling International (CRI), Mitsubishi Hitachi Power Systems, Hydrogenics

Characteristics: alkaline water electrolysis, methanol synthesis from H₂ and CO₂, CO₂ capture from a geothermal power plant

Description: The capacity of the power-to-methanol plant amounts to 4000 t of methanol per year (~2.5 MW methanol based on the LHV). The plant is co-operated by Carbon Recycling International (CRI) at Svartsengi, near Grindavik in Iceland. The methanol has been certified by SGS Germany using a protocol established by ISCC in February 2018. According to this certificate the use of renewable methanol from the George Olah Renewable Methanol Plant releases 90% less CO₂ than the use of a comparable amount of energy from fossil fuels.

Homepage: www.carbonrecycling.is



Figure 11: George Olah Renewable Methanol Plant, ThinkGeoEnergy, Licence CC BY 2.0, 2012

A2.2 MefCO₂ – Niederaussem, Germany

Status: Begin of operation in 2019

Participants:

- i-deals (Spain): Coordination, dissemination & exploitation.
- National Institute of Chemistry (Slovenia): Catalysis and reaction engineering.
- Mitsubishi Hitachi Power Systems Europe (Germany): System integrator.

- Cardiff Catalysis Institute (UK): Research in catalyst synthesis.
- Carbon Recycling International (Iceland): CO₂ to methanol technology developer.
- DIME - University of Genoa (Italy): Thermo-economic analysis and process optimisation.
- Hydrogenics Europe (Belgium): Electrolyser technology developer.
- University of Duisburg Essen (Germany): CO₂ capture technology provider.

Characteristics: alkaline water electrolysis, methanol synthesis from H₂ and CO₂, CO₂ from flue gas

Description: The plant will have a production capacity of 1 t of methanol per day (~230 kW of methanol based on the LHV) using 1.37 t of CO₂ and 0.19 t of H₂. The CO₂ is captured from flue gas from a coal power station.

Homepage: <http://www.mefco2.eu/news/visiting-mefco2-pilot-plant.php>

A2.3 Pilot plant from former Silicon Fire (now Swiss Liquid Future) – Altenrhein, CH (now in Oberhausen, Germany)

Status: in operation since 2010

Participants: Silicon Fire AG, Altenrhein (Kanton St. Gallen)

Characteristics: alkaline water electrolysis, methanol synthesis from H₂ and CO₂, CO₂ from sewage plant

Description: The capacity of the pilot plant amounts to about 1000 l of methanol per day (approximately 33 kg/hr). The commercial plant (model SLF 15) will have a capacity of 12 t of methanol per day (2.77 MW methanol based on the LHV). The required investment amounts to about € 35 million (12,600 €/kW_{methanol}) [Thyssenkrupp 2018]. The electricity input including H₂ production but without CO₂ supply is indicated with 6 MW, [Swiss Liquid Future 2019] leading to a power-to-methanol efficiency of about 46%. A project implementation agreement Me2Go signed to build 5 plants at hydropower sites in Switzerland [Thyssenkrupp 2018].

Homepage: <http://www.swiss-liquid-future.ch>



Figure 12: Pilot plant in Altenrhein, Kanton St. Gallen in Switzerland; the right picture shows the synthesis and the distillation column (picture: © Armin Grässl / Silicon Fire, 2011)

A2.4 WaStrak – Emschermündung, Germany

Status: Start of project in 2009; Begin of operation in September 2016; End of project 2017

Participants: Forschungsinstitut für Wasser- und Abfallwirtschaft an der RWTH (FIW); TUTTAHS & MEYER Ingenieurgesellschaft für Wasser-, Abwasser- und Energiewirtschaft mbH; Ingenieurbüro Redlich&Partner (IBR); Emschergenossenschaft

Characteristics: Electrolysis, methanol synthesis

Description: Methanol has been generated onsite a sewage plant in Emschermündung since September 2016. The methanol plant uses synthesis gas from steam reforming of desulphurised and dried biogas from the sewage plant plus hydrogen from water electrolysis.

Source: https://www.lanuv.nrw.de/fileadmin/forschung/190202_WaStrak_NRW/20181212_AB_WaStrak_II.pdf

Homepage: https://www.fiw.rwth-aachen.de/neo/index.php?id=594&tx_jppageteaser_pi1%5BbackId%5D=74

A2.5 FReSMe – From Residual Steel gases to Methanol, Sweden

Status: planned

Participants: Carbon Recycling International (CRI); Swerea MEFOS; SSAB (formerly: Swedish Steel); Tata Steel Netherlands; Kisuma Chemicals (Netherlands); Array Industries (Netherlands); ECN/TNO

Characteristics: H₂ from water electrolysis and off-gas (H₂, CO, CO₂) from steel production, methanol synthesis

Description: FReSMe stands for "From Residual Steel gases to Methanol". The project integrates the technology from two previous EU funded projects: STEPWISE, that is focused on the CO/CO₂ capture and conversion to CO₂+H₂, and MefCO₂, that involves power-to-methanol (chapter 2.4.2.3A2.2). The objective of the FReSMe project is to produce methanol for the ferry Stena Germanica (line Gothenburg – Kiel). The methanol will be produced from CO₂ recovered from an industrial blast furnace at SSAB in Luleå, and hydrogen recovered both from the blast furnace gas itself, as well as H₂ produced by electrolysis. The implementation of FReSMe encompasses:

- Lab developments supporting the technology improvement
- Modelling and simulation in order to optimize the processes
- Pilot plant construction and test campaigns implementation
- Life cycle analysis to evaluate the actual reduction achieved on GHG emissions

Homepage: <http://www.fresme.eu/>

A2.6 E2Fuels – Haßfurt (Bavaria), Germany

Status: Planned

Participants: Siemens, MAN Energy Solutions, Stadtwerke Haßfurt

Characteristics: power-to-methanol (PtL)

Description: In this project the production and use of synthetic fuels from renewable electricity for use in stationary and mobile applications is investigated.

In a first phase, a new methanol synthesis reactor is being designed (MAN Energy Solutions). Together with a 1.25 MW_e PEM electrolyser (Siemens Silyzer200) and CO₂ supply the new reactor will be operated at Haßfurt for demonstration. The system dynamics of this plant are analysed to optimise the operation with fluctuating renewable power supply. The results will be used to identify potential levers for technology up-scaling to bulk production size in future, for an in depth understanding of techno-economic details of the concept to ultimately achieve a commercial readiness.

In total, this project is carried out with 16 partners from industry and research.

The multi-million investment project receives co-funding from the Federal German Ministry for Economics and Energy (BMWi).

Homepage: <http://www.es.mw.tum.de/en/research/projects/e2fuels/>



A3 PETROL AND DIESEL VIA POWER-TO-LIQUID

A3.1 ALIGN-CCUS WP 4 – Niederaussem, Germany

Status: Begin of operation scheduled in November 2019

Participants: 31 companies, research institutes, and universities from 5 countries:

- Germany: Asahi Kasei Europe GmbH, FEV Europe GmbH, FZ Jülich, Mitsubishi Hitachi Power Systems Europe, RWE Power, RWTH Aachen University
- The Netherlands: Energy Research Centre of Netherlands, Maasvlakte CCS Project, Rijksuniversiteit Groningen, TAQA Energy, TNO, University of Leiden
- Norway: Bellona, IFE, NORCEM/Heidelberg Cement, NTNU, SINTEF M&C, SINTEF Petroleum Research, Technology Centre Mongstad, Tel-Tek, YaraRomania: CO₂ Club Association, GeoEcomar, NUSPA, PicOil
- UK: British Geological Survey, Heriot-Watt University, Imperial College London, Scottish Enterprise, Tees Valley Combined Authority, University of Edinburgh, University of Sheffield

Characteristics: Alkaline water electrolysis, methanol synthesis, DME synthesis, OME synthesis, CO₂ captured from flue gas from a coal power station

Description: As a global first-of-a-kind project, ALIGN-CCUS will build and test a fully integrated carbon capture and use (CCU) chain at pilot scale in a real industrial environment. The pilot will be constructed at RWE's Coal Innovation Centre in Niederaussem, Germany, where the company has operated a CO₂ capture system since 2009. The project will include an electrolysis plant with a capacity of 120 kW_e generating 25 Nm³ of hydrogen per hour. The captured CO₂ and hydrogen will then be converted to methanol-based products, DME and OME, in a synthesis unit provided by Mitsubishi Hitachi Power Systems Europe. DME and OME can be used as diesel fuel. The electrolysis plant is provided by Asahi Kasei. The project has a total operating budget of € 23 million. The European WAR-NET ACT Cofond supports the project together with other sponsors (e.g. the Bundesministerium für Wirtschaft und Energie in Germany) with € 15 million.

Homepage: <https://www.alignccus.eu/about-project/work-package-4-co2-re-use>

A3.2 Sundance Clean Methanol – 23 km east of Chetwynd in north-eastern British Columbia, Canada

Status: Planning, permitting

Participants: Blue Fuel Energy, Siemens, McPhy

Characteristics: PEM based water electrolysis added to a gas-to-liquid (GTL) plant, methanol synthesis, methanol-to-gasoline (MtG), CO₂ captured from a natural gas fuelled power plant with oxy burner (O₂ from electrolysis plant).

Description: The capacity of the electrolysis plant will amount to 20 MW_e [Siemens 2014]. The electricity is supplied by wind turbines nearby the facility. Besides hydrogen from the electrolysis plant synthesis gas from autothermal reforming (ATR) of natural gas is used as feedstock. The natural gas requirement will amount to about 3.8 million Nm³ per day (~1,580 MW of natural gas). Products are gasoline and LPG. The methanol-to-gasoline plant will have a capacity of 16,000 barrels of gasoline per day (2,544 m³/d ~ 1,900 t/d~ 950 MW gasoline based on the LHV) [Stantec 2016], [Blue Fuel Energy 2019]. The investment is indicated with CAN\$ 2.5 billion. It has been communicated that a hurdle for the project is to find laborers for the construction of the plant located far away from cities [Blue Fuel Energy 2015].

Homepage: <http://bluefuelenergy.com/>

A3.3 Sunfire PtL – Dresden, Germany

Status: In operation

Participants: Sunfire, Climeworks, Audi

Characteristics: High temperature electrolysis using solid oxide electrolysis cells (SOEC), direct CO₂ capture from air (DAC), reverse water gas shift (RWGS), Fischer-Tropsch synthesis

Description: In autumn of 2014, a demonstration plant was inaugurated in Dresden (Germany). The installed production capacity is about 1 barrel per day of crude PtL from Fischer-Tropsch synthesis. The concept comprises a high-temperature (solid-oxide) electrolyser using excess heat from Fischer-Tropsch synthesis. Electricity demand is thus reduced, increasing the PtL production efficiency (fuel output vs. electricity input).

Homepage: <https://www.sunfire.de/en/company/news/detail/sunfire-produces-sustainable-crude-oil-alternative>

A3.4 Nordic Blue Crude – Herøya, Norway

Status: Planned

Participants: Nordic Blue Crude, Climeworks, Sunfire, EDL Anlagenbau

Characteristics: power-to-synchrude

Description:

2019-01-01: Sunfire began the process of scaling-up the high-temperature co-electrolysis process to an industrial scale – initially with an input power of 150 kW (DC) – as part of



the 'SynLink' project (03EIV031A) funded by the Federal Ministry of Economics and Energy. This multipliable co-electrolysis module is to be used by Nordic Blue Crude, the Norwegian project partner. The first commercial plant is to be built there, and will produce 10 million litres or 8,000 t of the synthetic crude oil substitute (e-syn crude) annually on the basis of 20 MW_{e,in}.

Source: <https://www.sunfire.de/en/company/news/detail/breakthrough-for-power-to-x-sunfire-puts-first-co-electrolysis-into-operation-and-starts-scaling>

2017-07: From 2020 the first plant shall start its operation in the industrial park Herøya in Norway. It will be operating with an electric capacity of 20 MW, producing 8,000 t/a syn crude. Nordic Blue Crude AS, Sunfire, Climeworks, EDL Anlagenbau and additional partners have started with the engineering. Part of the CO₂ is extracted on-site from the ambient air using the Direct Air Capture (DAC) technology (Climeworks). The syn crude consists of various hydrocarbons, making it comparable with crude oil. Refineries can use it as raw material for waxes, but also petrol, diesel, kerosene. The target-price per litre lies below 2 €.

Source: <https://www.sunfire.de/en/company/news/detail/first-commercial-plant-for-the-production-of-blue-crude-planned-in-norway>

Homepage: <https://www.nordicbluecrude.no>

A3.5 KEROSyN100 – Heide (Schleswig-Holstein), Germany

Status: Announced as per July 2018

Participants: Chemieanlagenbau Chemnitz GmbH, Raffinerie Heide GmbH, SKL Engineering & Contracting GmbH, TU Bergakademie Freiberg, Deutsche Gesellschaft für Luft- und Raumfahrt (DLR), Institut für Vernetzte Energiesysteme e.V., Lufthansa (off-take agreement)

Characteristics: Power-to-liquids (synthetic jetfuel)

Description:

Phase 1: Plant design and basic engineering for the conversion of methanol from renewable power to jetfuel (power-to-jetfuel).

Phase 2: Realisation of a demonstration plant at the Heide refinery.

Project funding request titled „KEROSyN100: Entwicklung und Demonstration einer dynamischen, effizienten und skalierbaren Prozesskette für strombasiertes Kerosin – **Phase 1**“ with € 4.2 million over three years from the German Federal Ministry for Economics and Energy (BMWi) in the framework of „Energiewende im Verkehr: Sektorkopplung durch die Nutzung strombasierter Kraftstoffe“.

Sources:

- <https://www.internationales-verkehrswesen.de/forschungsprojekt-kerosyn100/>
- <https://www.res.uni-bremen.de/index.php?id=85>
- <https://www.uni-bremen.de/de/universitaet/presse/pressemitteilungen/detailansicht/news/detail/News/zukunftstraum-mit-gr%C3%BCnem-treibstoff-fliegen/>

Homepage: <https://www.res.uni-bremen.de/index.php?id=85>

A3.6 GreenPower2Jet (GP2J) – Stade/Lingen (Lower Saxony), Germany

Status: Announced as per April 2019

Participants: Airbus, BP Lingen, BP Air, Dow, DLR, Hoyer Logistik, Easyjet, DHL, et al.

Characteristics: Power-to-liquids (synthetic jetfuel)

Description: The aim of the project 'GreenPower2Jet' (GP2J), after successful pre-engineering, is to build an industrial-scale power-to-liquid plant (PtL) which will primarily supply sustainable synthetic hydrocarbons to be used in producing green, climate-neutral jet fuels.

The project consortium includes the Technical University of Hamburg (TUHH, for project coordination), Airbus, BP (BP Lingen, Air BP), the German Aerospace Centre (DLR), Dow and Hoyer Logistik and, as potential customers for the fuel produced, DHL, easyjet, supported by the Hamburg Airport, GDH Transport und Containerlogistik, and the Flotte Hamburg (a subsidiary of Hamburg Port Authority).

The plan is to put the idea of the project into practice over a funding period of five years.

In the first step, after a six-month pre-engineering phase lasting until 2021/22, an industrial-scale PtL plant (based on so-called Fischer-Tropsch synthesis) can, in agreement with the partners, be built in Stade, at the DOW chemical company. The synthetic hydrocarbons produced there are to be delivered to BP's refinery in Lingen, where they will be processed as the basis for the next production steps and then used to produce green, climate-neutral jet fuel. The plan is to use this fuel at Hamburg Airport on routes which are flown regularly, as well as for the first fuelling of Airbus planes in Hamburg-Finkenwerder. In addition, "green" diesel is to be produced from the leftover by-products, and this diesel can be used in heavy goods vehicles and in the port of Hamburg, in the ships which regularly operate there. By today's standards, none of the products from the portfolio produced can be manufactured economically, which means that regulatory incentives and funding are necessary in order for this technology, which is important for meeting the challenging targets for the reduction of GHGs, to continue to be developed.

Homepage:

https://intranet.tuhh.de/aktuell/pressemitteilung_einzeln.php?Lang=en&id=12037

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Ludwig-Bölkow-Systemtechnik GmbH

Daimlerstrasse 15 · 85521 Ottobrunn · Germany
phone: +49 89 6081100 · fax: +49 89 6099731
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