European Commission

LOW CARBON ENERGY OBSERVATORY

ADVANCED ALTERNATIVE FUELS

Technology development report

Joint Research Centre

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Contents

Foreword on the Low Carbon 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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1 Introduction

This is the second iteration of the Technology Development Report for Advanced Alternative Fuels. As will be seen from this report, the fuel production pathways studied tend to be 'ground-breaking' or relatively new, with much work being carried out at laboratory scale. While that means projects tend to be at low-TRL, it is possible they could become applicable at higher TRL levels. When seeking to define what constitutes an advanced alternative fuel (AAF), a number of important sources have been referred to. Principally, the SET-Plan Integrated Roadmap description has been used as the main guide to define the fuel types considered. The roadmap states such fuels represent *new technological concepts for the introduction of non-biomass and non-fossil based alternative fuels in transport*. This includes:

- CO_2-based and CO_2-neutral liquid and gaseous fuels such as methanol, ethanol, green gas or other fuel molecules using renewable energy, and
- Artificial photosynthesis and fuel from photosynthetic microorganisms (in water and land environments) and from artificial photosynthesis mimics (SET-Plan Integrated Roadmap, 2014).

Hydrogen holds great promise as an important fuel in itself, and one in which there is currently a considerable amount of interest both in the EU and across the globe. For example the Fuel Cell and Hydrogen Joint Undertaking[1] (FCH JU), with an EU contribution of some EUR 665 million under H2020, shows the level of interest and prioritisation being applied to the use of hydrogen as a fuel.

However, the use of hydrogen itself as a fuel is not a focus here. This report is concerned with the use of hydrogen as a 'feedstock' with which to make other fuels. Some broad information on the production of hydrogen is given as a summary, as it is such an important ingredient for many of the fuels discussed within this report. But interested readers wishing to know more about hydrogen as a fuel, including aspects related to its production, storage, transportation and use in fuel cells, and to get a full picture on research efforts being conducted in this technology are directed to the extensive 'Fuel Cells and Hydrogen' LCEO TDR, D2.1.13.

In a similar fashion to H_2, this TDR is concerned with the use of CO_2 or carbon containing gases to make other fuels – although a brief overview on CO_2 technologies is again provided herewith. Readers wishing to get a detailed picture on carbon capture, utilisation and storage are kindly directed towards the LCEO TDR D2.2.9 'Technology development report on Carbon Capture Utilisation and Storage (CCUS)'.

Returning to the consideration of the definition of advanced alternative fuels for the purposes of this report, the recast of the Renewable Energy Directive (RED) (2009/28/EC) was published in December 2018 (EU 2018/2001). It contains two new types of advanced alternative fuels which Member States (MS) can choose to promote, namely:

- Recycled carbon fuels and
- Renewable fuels of non-biological origin

Renewable fuels of non-biological origin are liquid or gaseous fuels, used in transport (*and not biofuels*) whose energy content comes from renewable energy sources other than biomass. Generally, it is expected the energy for these fuels would come from renewable electricity, so-called electrofuels. The other category, 'recycled carbon fuels' are defined as 'liquid and gaseous fuels produced from liquid or solid waste streams of non-renewable origin which are not suitable for material recovery, or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations (Directive EU 2018/2001).

[1] https://www.fch.europa.eu/

Degree of renewability

Structuring or grouping the technological pathways on the basis of their potential to be renewable (or otherwise) is indeed challenging. For example, power to fuel (PtF) can be both a renewable and partially a bio-fuel, if the H_2 is produced from RES (renewable energy sources) electricity, and the carbon in the CO_2 is of biological origin (e.g. from biogas upgrading to biomethane). On the other hand, PtF can be produced using RES energy blended with some electricity from the grid, thus not entirely renewable electricity is used as an input, but such a situation may be necessary to allow the fuel facility to continue production during periods of low-renewable electricity availability. Also the carbon used as a feedstock for some processes may not be only biological carbon, it could be fossil carbon also, depending on where and how the fuel production facility is set up.

On the basis of these considerations, in preparing this report, the authors decided to approach the problem from a technical point of view. The technologies have been grouped generally according to the SET-Plan description, while allowing consideration under the RED recast. The focus has been on renewable pathways, but we noted some pathways could be partially renewable, depending on their feedstock/power source. The most notable of these would be the so-called recycled carbon fuels whose projects have generally been focussed on recycling fossil type carbon sources.

Technological areas considered

In some cases, a fuel pathway can employ both power to fuel technology and the use of CO_2. Indeed, PtF has two large sub-groups, related to the production of the main process inputs, H_2 and CO_2, while microbial fermentation focuses on the use of carbon containing gases as feedstocks for microbes, which subsequently produce a liquid fuel.

Nonetheless, in order to be coherent with the SET-Plan roadmap, the RED recast, and to match the broad categories of technological areas the reviewed H2020 projects fit into, the work areas have been categorised as follows (please see also Table 1 below):

- Power-To-Fuels, or electrofuels, includes water-splitting/artificial photosynthesis fuels[2]. This is a very broad title, and some of the projects investigated describe a 'sub-aspect' of this category. It represents the majority of work considered. It begins by looking at the provision of the main materials considered feedstocks in this report, namely H_2 and CO_2, followed by a section looking at fuel synthesis steps.
- Microbial fermentation; a smaller category, describing a relatively new technology proposed principally by one company, but there appears to be quite a degree of interest in this pathway. How it progresses – having appeared to have made useful steps towards large-scale production remains of interest. It considers carbon from non-bio sources, but it is applicable nonetheless to using carbon from biomass.

[2] Fuels from photosynthetic microorganisms (microalgae) are already in the LCEO – Technology Development Report Sustainable Advanced Biofuels, Deliverable D2.2.12

Table 1. Relevant technological pathways

Technologies:
Power to fuel (electrofuels)
H_2 production using renewable electricity *
Alkaline electrolysis
Solid-oxide electrolysis cell (SOEC)
PEM (Proton exchange membrane) electrolysis
Water-splitting/artificial photosynthesis
CO_2 capture using renewable electricity
Waste high concentration CO_2 from renewable sources **
Amine-based post combustion capture **
Fuel Synthesis (methanol, synthetic petrol or diesel, methane)
Microbial fermentation
Industrial off-gases processed by bacteria into ethanol
Mixture of sewage gas and natural gas processed by bacteria into ethanol

* Production aspects of H_2 are summarised below, but for a comprehensive report on this topic interested parties are referred to the Hydrogen & Fuel Cells TDR D2.1.13.

** These aspects are summarised below, while a comprehensive picture on these technologies is available in the 'Carbon Capture, Utilisation and Storage' TDR D2.2.9.

Further note on recycled carbon fuels

The RED recast considers recycled carbon fuels as non-renewable, because the main sources considered for the carbon inputs have been fossil. Nonetheless, the new RED recognises these fuels can contribute towards transport decarbonisation, if they reach appropriate greenhouse gas (GHG) savings compared to regular fossil fuels. Both the methodology for calculating any such GHG savings for these fuels – and indeed for PtF's – is under development by the Commission. Member States can use these fuels towards the overall EU-target for energy from renewable sources (Directive EU 2018/2001). Such systems which transform fossil carbon containing off-gases into liquid fuels, will therefore be noted separately in this report as for now, they are predominantly non-renewable fuels. Other descriptors for non-renewable fuels are available in literature; E4Tech (2018) in a report for the UK Government, described a range of fuels from non-renewable sources, but which do provide GHG savings, as 'low carbon fossil fuels (LCFFs)'. They considered fossil based fuels which do not provide emissions reductions compared to the 94g CO_2 fossil fuel comparator, as simply alternative fossil fuels.

The fuels in this report represent comparatively new technologies

Finally, compared to biofuels (advanced or conventional), the authors note these fuels represent technology chains which generally remain as emerging, and have not yet, or are only beginning to enter large-scale or industrial scale production, in limited or single sites, both in the EU and elsewhere. Therefore information may in some cases be relatively scarce, but nonetheless, a comprehensive attempt at their description has been carried out. It is likely that in the coming years, more information will be available, and it is certainly a growing area which warrants further investigation and monitoring. Advanced alternatives aim to provide important benefits, and hope to avoid some of the problems associated with other fuel production pathways, such as the need for land and input requirements for making biomass, or indeed they try to improve on the efficiency of natural functions (such as plant photosynthesis).

1.1 Methodology

In this report, we focus on state-of-the-art, ongoing and future R&D needs of power-to-fuel (and artificial photosynthesis) processes, using hydrogen from renewable energy and CO_2, and further, on microbial fermentation processes, to make fuels for use in the transport sector. Hydrogen in its use as a fuel is outside the scope of this report but is considered from the point of view of its use as a feedstock to make other fuels.

The research focussed initially on advanced alternative fuel technologies which have technological readiness levels (TRLs) approaching commercial relevance, but due to the emerging nature of these fuel production pathways, it was found that most development is happening at lower TRLs. The information on projects has been collected from the CORDIS website and the project's websites where available. Relevant keywords have been used to define proper queries in the tools, in order to identify projects, under the Horizon 2020 (H2020) programme. Further analysis, to describe objectives and main achievements was conducted, in order to define the projects impact on the technology development. A search was carried out for relevant national projects and SET-Plan 'flagship projects/activities', provided by the Temporary Working Group (TWG) on the 'Implementation Plan for the SET-Plan Action 8 on Bioenergy and Renewable Fuels for Sustainable Transport' and have been included in the analysis. Flagship activities are defined in the Implementation Plan as "prominent on-going R&I activities contributing to achieving the (SET Plan) targets and of interest to the public at large"; a flagship activity can be a project or programme with an innovation potential and the capacity to "lead by example" (Implementation Plan, Action 8, 2018). Most of the projects under analysis are on-going and therefore the assessment of their impact is limited to the available deliverables.

1.2 Data sources

In addition to the above-mentioned information sources, the main sources used to analyse the sector's state-of the-art and to identify advanced alternative fuel technologies plants (if any, either at pilot, demo or other stage) were, through expert's scientific publications, information gained through the JRC's own work on this topic, plants' websites, and also linked LCEO reports, as some technologies described here have partially been the focus of other TDRs. The identification of technologies status worldwide, as well as technical barriers and potential challenges to the large-scale deployment of advanced alternative fuels has been based on major international studies and peer-reviewed papers.

1.3 Legislative context

European legislation, in particular that linked to GHG savings in the transport sector, is beginning to recognise advanced alternative fuels, which could help their progression onto the market.

The **Renewable Energy Directive recast** (EU 2018/2001) or RED2 contains a 14% target for renewable energy in transport, an increase from the previous 10% target. It encourages the continuous development of alternative renewable transport fuels which now includes renewable liquid and gaseous transport fuels of non-biological origin (and renewable electricity in transport). New alternative fuels, are seen as an up and coming possibility to help decarbonise the transport sector, still dependent on liquid fuels, and it is possible for MS to promote these fuels. Existing alternatives have their own restrictions because of well-known issues: conventional biofuels for e.g., once seen as a key part of reducing GHG emissions, have been limited in RED2 - at national level at 2020 values +1%, but are capped at 7% on an energy basis. Moreover, advanced biofuels are subject to a specific sub-target, or, if produced from feedstocks listed in annex IX part b, they count only up to 1.7% towards the overall 14% target. Therefore, new alternative fuels are increasingly being encouraged, namely *recycled carbon fuels*, and *renewable fuels of non-biological origin*.

The RED2 recognises recycled carbon fuels can contribute towards the policy objectives (of energy diversification and transport decarbonisation) when they fulfil the appropriate minimum greenhouse gas (GHG) savings threshold (which the Commission must decide upon and publish before 2021). RED2 considers it appropriate to include those fuels in the obligation on fuel suppliers (to use a minimum amount of renewable energy in their fuels), whilst giving Member States the option not to consider these fuels in their obligations. Renewable fuels of non-biological origin can contribute to low carbon emissions, stimulating decarbonisation of transport, and improving energy diversification in transport, amongst several other positive aspects, and the RED2 considers these fuels can increase the share of renewable energy in sectors that are expected to rely on liquid fuels in the long term. For example, the communication of the Commission of 20 July 2016 entitled "**A European Strategy for Low-Emission mobility**" highlighted the particular importance, in the medium-term, of advanced biofuels and fuels of non-biological origin for aviation. It highlights that in order to ensure such fuels contribute to GHG reductions the electricity used in their production must be renewable. More recently, the new **European Green Deal**[3] published in December 2019, notes that as well as clean hydrogen, "other alternative fuels" will be necessary to help the EU deliver the green deal.

Renewable fuels from non-biological origin can be produced **using peaks** in the RES production, consequently potentially increasing the renewable energy plant's availability. Otherwise, if grid electricity is used, it is proposed that a reliable methodology (under development by the Commission) should be used to properly assess the impact on the grid and the resulting emissions. For example, RED2 states renewable fuels of non-biological origin can't count as fully renewable if produced when the renewable generation unit is not generating electricity. Critically, it notes the concept of **additionality**, i.e. the fuel producer should be adding to renewable deployment (or to the financing of renewables) (EU 2018/2001).

Not directly linked to advanced alternative fuels, the authors nonetheless note the directive on the deployment of alternative fuels infrastructure (2014/94/EU) describes 'alternative fuels' as fuels or power sources which serve (at least partly) as a substitute for fossil oil sources in the energy supply to transport, and *which have the potential to contribute to its decarbonisation*. The alternatives described include electricity, hydrogen, biofuels, synthetic and paraffinic fuels, natural gas (& biomethane) both gaseous and compressed (CNG) and liquefied form (liquefied natural gas (LNG), and liquefied petroleum gas (LPG).

1.3.1 Note on GHG emissions savings

Unlike the methodology for traditional biofuels GHG evaluation as per current legislation, a different methodology – under development at time of writing – will be applied to define the GHG intensity of advanced alternative fuel pathways. The principles upon which such calculations will be based are described in a guidance document prepared by JRC (JRC, 2016). The approach moves beyond the traditional attributional approach: where the supply of input (feedstock) is rigid (i.e. the overall supply of the input cannot be expected to expand to meet increased demand), the GHG of the input should be assessed by considering the impact of removing a quantity of that input from its **current use** (also commonly referred to as 'displacement'). Such emissions could in theory be also negative. This important distinction is especially relevant when considering electrical inputs to a fuel production system. But where the supply of the input is elastic (i.e. its supply can be expanded to meet increased demand), the GHG of the input should be assessed through an attributional lifecycle assessment of its production process (JRC, 2016). Searle (2018) in a study on the decarbonisation potential of electrofuels, states that car-maker associations are advocating the possible GHG savings from such fuels could even count

[3] https://ec.europa.eu/info/publications/communication-european-green-deal_en

towards lowering the CO_2 emissions of vehicles themselves. Finally, while GHG emissions arising during the manufacture and construction of renewable electricity systems can be low, and are in general expected to continue to fall, it may be an aspect which requires further consideration, as the electricity demand for electrofuel facilities can be large.

2 Technology state of the art and development trends

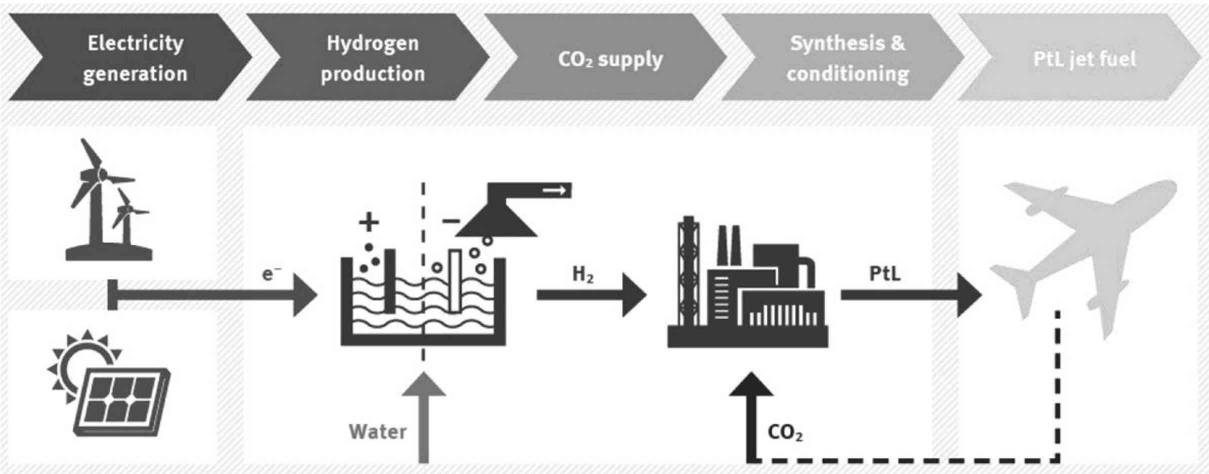
As described in the introduction, this is the second iteration of the Technology Development Report for 'Advanced Alternative Fuels'. The pathways analysed are summarised in Table 1.

2.1 Power to Fuel or Electrofuels

The three main constituents of power-to-fuels are electricity, CO_2 and water, producing a gaseous or liquid fuel. The fundamental technological steps for electrofuel production are (a) **electrolysis**, in which water is broken down into hydrogen and oxygen with the use of electrical energy, and (b) **chemical fuel synthesis** in which hydrogen is reacted with the carbon from carbon dioxide to produce more complex hydrocarbons (Cerulogy, 2017).

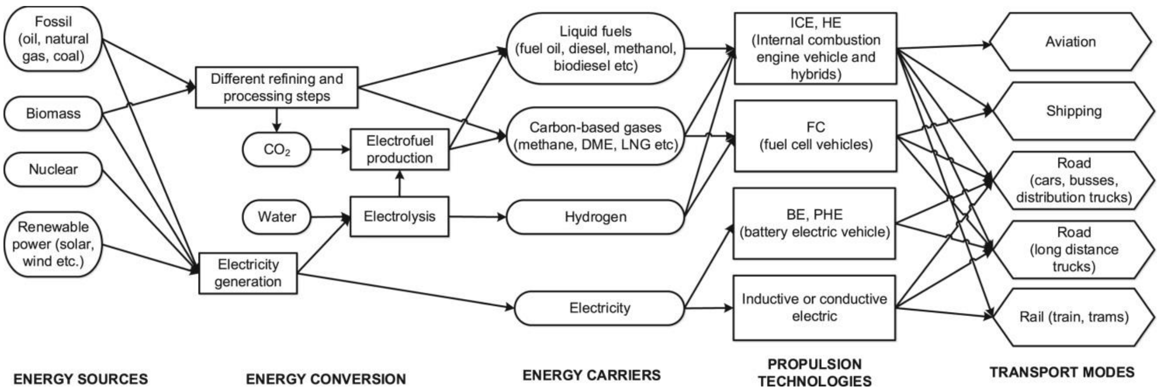
This conversion of electricity (via water electrolysis), and subsequent synthesis (with CO or CO_2) into a gaseous or liquid fuel, potentially enables a coupling of various sectors, which in turn can offer strategic advantages for the whole energy system. Power-to-Gas (PtG) and Power-to-Liquids (PtL) are often discussed as important elements in a future renewable energy system (Buttler & Spliethoff, 2018). This opens enormous storage or absorption capacities for excess energy with high electricity generation from renewable energies in excess of demand. It also supports the integration of fluctuating renewables like wind and solar power in the energy system, including the provision of balancing power.

Figure 1. Generic scheme for PtL production (source Schmidt et al., 2018)



Interestingly, many of the technological steps required for liquid electrofuel production are already widely used in other industrial applications, while some parts of the Power-to-fuel chain have lower TRLs. Despite the on-going activities, some authors (i.e. Cerulogy, 2017) consider that full process from electricity to synthetic fuel has never been demonstrated at commercial scale (although pilot scale facilities exist). Searle (2018) in a dedicated electrofuels study note they expect limited if any, renewable fuel volumes and GHG reductions from electrofuels in the EU, at least up to 2030. Interest in these fuels remains strong, for example Bosch, the large German automotive engineering company published a short overview promoting electrofuels, and noting that around half the vehicles that will be on the road in 2030 have already been sold, and these predominantly have gasoline or diesel engines (Bosch, 2019).

Figure 2. Potential pathways implying PtX processes (source (Brynolf et al., 2018)*)

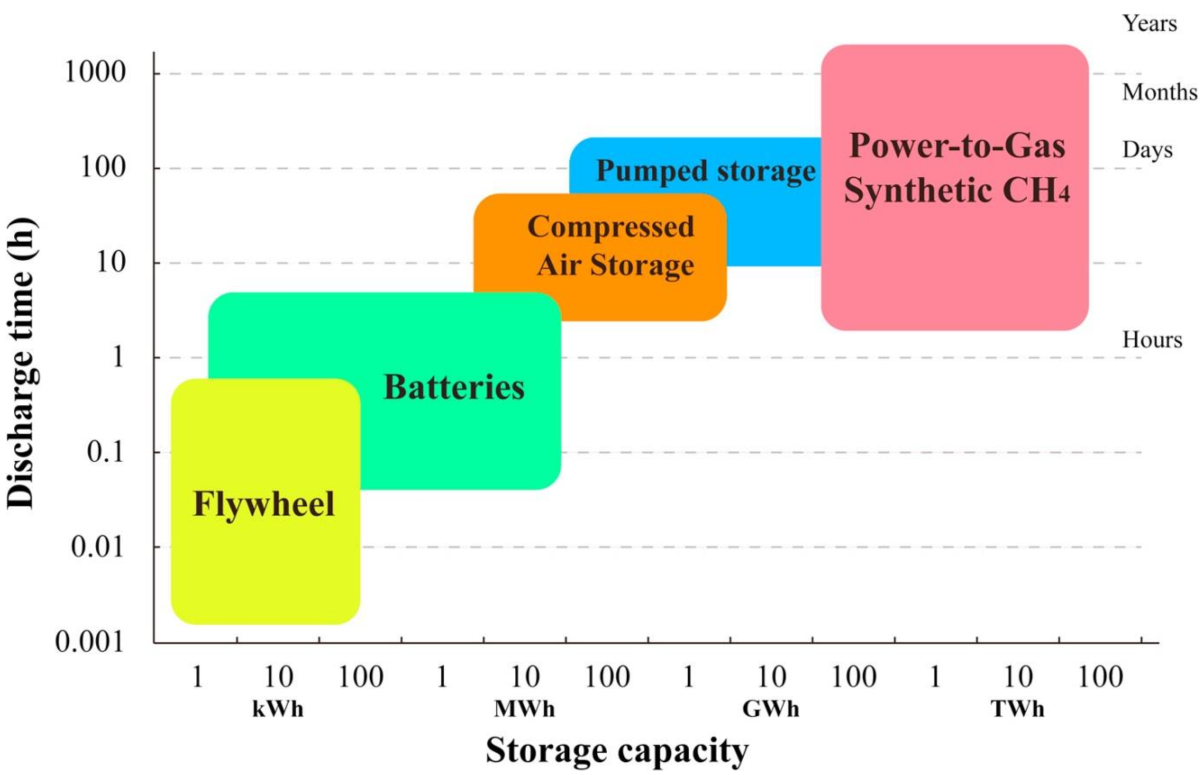


* A further option for hydrogen production can be via the concentrated solar thermochemical process, which has the advantage of avoiding the need to produce electricity, and in theory having a higher efficiency as one uses most of the entire incoming energy.

As already indicated, something crucial for the future development of PtX is the possibility to act as storage for balancing fluctuating RES (Blanco & Faaij, 2018). PtG and PtL are options complementing the common application of storage for short-term applications and balancing of variable RES fluctuations with a long-term (seasonal) function. Blanco & Faaij (2018) further pointed out that the role of storage becomes more relevant for variable RE penetration higher than 30%, as below this threshold curtailment is usually the best option. A schematic showing the potential storage capacity of Ptx is provided in Figure 3.

The rest of the chapter thus broadly introduces the concept of H_2 production from renewable electricity, followed by describing the principle methods of CO_2 capture, and then focusses on the fuel synthesis steps from these feedstocks; namely Power to Gas and Power to Liquids production.

Figure 3. Storage capacity of PtG (source Ma et al. (2018))



2.1.1 Electrolysis: H_2 production using renewable electricity

The aim of this section is to provide an overview of how H_2 can be produced from the electrolysis of water, using renewable electricity as a power source. As this topic has been comprehensively described in another LCEO TDR (Deliverable D2.1.13 *Fuel Cells and Hydrogen, 2016*), but it is critical for the description of the fuel production pathway here, we provide a brief summary directly from D2.1.13, and our own other research and literature reviews, focussed on the subsequent fuel production aspects.

2.1.1.1 Introduction to the process

Electrolysis is an old technology, beginning as far back as the early 1890's; today, electrolysers are working at full industrial scale, some using over 100 MW of electrical power input. Currently the main water electrolysis technologies are Alkaline Electrolysis (AEL), Polymer Electrolyte Membrane Electrolysis (PEMEL) and Solid Oxide Electrolysis (SOEL) (Buttler and Spliethoff, 2018). PEM and alkaline type electrolysers are low temperature in operation. High temperature electrolysis is also available which uses steam, and which has the effect of reducing the electrical input needed for electrolysis. Solid Oxide Electrolyser Technology (SOEL) type electrolysers use this high temperature approach (Schmidt et al, 2018).

2.1.1.2 Electrolysis state of the art

In Deliverable D2.1.13, the JRC scientific and technical report on the assessment of hydrogen and fuel cell technologies developed as part of the SET-Plan report series provides a good overview of the technology state-of-the-art (SoA) of alkaline and PEM electrolysers (Cerri, 2015), and a similar but more recent study can be found in Thema et al (2019).

Table 2 Overview Electrolyser SoA (source LCEO TDR D2.1.13)

Electrolysers	Alkaline	PEM
Technology status	Mature technology	Mature technology
T range (°C)	ambient - 120	ambient - 90
Electrolyte / pH	25-30 wt.% (KOH)aq	Perfluorinated sulfonic acid (PFSA)
Mobile species	OH-	H3O+
Cathode catalyst	nickel foam/ Ni-Stainless Steel	platinum
Cathode carrier / support	nickel foam/ Ni- Stain-less Steel Ni-Mo/ZrO2-TiO2	carbon
Anode catalyst	Ni2CoO4, La-Sr-CoO3, Co3O4	Ir/Ru oxide
Anode carrier / support	-	-
Separator	asbestos, PAM, ZrO2-PPSF, NiO, Sb2O5-PS	electrolyte membrane
Sealant	metallic	synthetic rubber or fluo-roelastomer
Current distributor	Ni	titanium
Containment material	nickel plated steel	stainless steel
P range (bar)	1 – 200	1 – 350 (700)
Operational current density (A/cm2)	0.2 – 0.5	0 - 3
Efficiency (%) (at i A.cm-2/ Ucell V/ T°C)	60-80 0.2-0.5 / 2.0 / 80	80 1.0 / 1.8 / 90
Capacity (Nm3/hour)	1 – 500	1 - 230
Durability (hours)	100 000	10 000 – 50 000
H_2O specification	liquid	ρ > 10 MΩ.cm
Load cycling	medium	good
Stop/go cycling	weak	good

The performance requirements for these applications can be translated into KPIs: efficiency/energy consumption, degradation, investment cost, operational flexibility, start/stop response. The Fuel Cells and Hydrogen (FCH) JU's multi-annual work program (MAWP 2014-2020) contains an overview of the targets set for key performance indicators (KPIs) for decentralised electrolyser systems (see Table 3). The values for 2012 express the SoA of the technology and final targets are defined for 2023.

Table 3 Electrolyser targets FCH JU (source LCEO TDR D2.1.13)

EU - KPI's, SotA and future targets for decentralized electrolyser systems (FCH JU)[18]					
		2012	2017	2020	2023
Energy consumption (system)	**kWh/kg**	**57-60**	**55**	**52**	**50**
Efficiency (system, LHV)	*%*	*56-58*	*61*	*64*	*67*
CAPEX (installed system costs)	**k€/(t/d)**	**8000**	**3700**	**2000**	**1500**
CAPEX (installed system costs)	*€2013/kW*	*3368 - 3200*	*1615*	*923*	*720*
Degradation (efficiency degradation	**%/year**	**2-4**	**2**	**1.5**	**<1**
@ rated power and considering 8000 hours of operation per year)					
Operational flexibility (with < 2% degradation per year)	**% of nominal power**	**5-100**	**5-150**	**0-200**	**0-300**
Hot start (minimum to maximum power)	**seconds**	**60**	**10**	**2**	**<1**
Cold start	**seconds**	**300**	**120**	**30**	**10**

Buttler and Spliethoff (2018) published a review paper on the status of water electrolysis for energy storage. The authors reported that electrolysers feature an increase in performance in part-load. Rated efficiency and specific energy consumption of commercial electrolysis stacks are in the range of 63–71% LHV and 4.2–4.8 kWh/Nm3 for AEL and 60–68% LHV and 4.4–5.0 kWh/Nm3 for PEMEL (based on the next table). The authors indicated the specific energy consumptions of electrolysis systems (including rectifier and utilities, excluding external compression) are in the range of 5.0–5.9 kWh/Nm3 (LHV = 51–60%) for AEL and 5.0–6.5 kWh/Nm3 (LHV = 46–60%) for PEMEL. They further note reduced performance at lower capacity is observed for electrolysis systems below a hydrogen production rate of approx. 100 Nm3/h (0.5 MW), mainly due to the decreasing efficiency of the utilities.

Table 4. Summary of parameters of state-of-the-art of water electrolysis technologies. (source Buttler and Spliethoff (2018))

	AEL	PEMEL	SOEL
Operation parameters			
Cell temperature (°C)	60–90	50–80	700–900
Typical pressure (bar)	10–30	20–50	1–15
Current density (A/cm^2)	0.25–0.45	1.0–2.0	0.3–1.0
Flexibility			
Load flexibility (% of nominal load)	20–100	0–100	−100/+100
Cold start-up time	1–2 h	5–10 min	hours
Warm start-up time	1–5 min	< 10 s	15 min
Efficiency			
Nominal stack efficiency (LHV)	63–71%	60–68%	100%[a]
...specific energy consumption (kWh/Nm^3)	4.2–4.8	4.4–5.0	3
Nominal system[b] efficiency (LHV)	51–60%	46–60%	76–81%
...specific energy consumption (kWh/Nm^3)	5.0–5.9	5.0–6.5	3.7–3.9
Available capacity			
Max. nominal power per stack (MW)	6	2	< 0.01
H_2 production per stack (Nm^3/h)	1400	400	< 10
Cell area (m^2)	< 3.6	< 0.13	< 0.06
Durability			
Life time (kh)	55–120	60–100	(8–20)[c]
Efficiency degradation (%/a)	0.25–1.5	0.5–2.5	3–50
Economic parameter			
Investment costs (€/kW)	800–1500	1400–2100	(> 2000)[c]
Maintenance costs (% of investment costs per year)	2–3	3–5	n.a.

[a] Operating at thermoneutral voltage.
[b] Including auxiliaries and heat supply (SOEL).
[c] High uncertainty due to pre-commercial status of SOEL.

Lifetime is another important parameter for the economic analysis of electrolysis systems, as voltage degradation results in reduced performance during operating life. Regarding the lifetime of an electrolyser, it has to be distinguished between the stack and the plant. Balance of plant has a typical lifetime of about 20 years for SOEL and PEMEL with up to 30–50 years stated for stationary operated AEL.

Table 5. Overview of commercial electrolysis systems

(Please note, these are not exhaustive, only the largest systems from each supplier are listed) – source 'Overview of commercial electrolysis', (Buttler and Spliethoff, 2018). More useful information is available in Thema et al (2019) although their study is focused on PtG, and they note many of the systems they list are pilot scale and with short life-spans.

Manufacturer (location)	Series	H_2 rate, Nm^3/h[a]	Nominal power, MW[a]	Max. pressure, bar	Specific energy consumption[a,b], kWh/Nm^3	η_{LHV}[a,b,c]%	Load flexibility (%)
Alkaline electrolysis (AEL)							
ELB (DE)	LURGI SE[d]	1400	6.0	30	4.3–4.65	65–70	25–100
Suzhou Jingli (CN)	DQ 1000	1000	4.7	16	4.7	64	10–110
Verde (US)	Verde – 1000	1000	4.5	30	4.2	79	n.a.
IHT (CH)	S – 556[d]	760	3.5	32	4.3–4.65	65–70	25–100
PERIC[e] (CN)	ZDQ – 600	600	2.8	15	4.6	65	n.a.
NEL Hydrogen[f] (NO)	NEL A485	485	2.1	atm.[g]	3.8–4.4	68	20–100
ELB(DE)	ELB ND4	480	2.0	atm.[g]	4.3–4.6	71	25–100
Teledyne[h] (US)	NH – 450	450	2.7	10	(5.9[i])	(51)	17–100
McPhy[j] (FR)	McLyzer	400	2.0	atm.[g]	n.a.	n.a.	n.a.
Tianjin Mainland (CN)	FDQ – 400/3.0	400	1.76	30	< 4.4	68	n.a.
Ener Blue (CH)	L-size	375	1.6	60	4.3	70	n.a.
ELB(DE)	BAMAG S300E	330	1.5	atm.[g]	4.7	64	25–100
Uralhimmasch (RU)	BEU – 250	250	n.a.	10	n.a.	n.a.	n.a.
HT-Hydrotechnik (DE)	EV 150	220	1.1	atm.[g]	(5.3)	(57)	20–100
Uralhimmasch (RU)	FV – 200	200	n.a.	atm.[g]	n.a.	n.a.	n.a.
McPhy [j] (FR)	McLyzer	100	0.5	45	n.a.	n.a.	n.a.
Idroenergy (IT)	Model 120	80	0.4	6	(5.6)	(54)	n.a.
ETOGAS (DE)		62.5[k]	0.3	15	4.8	63	10–110
Green Hydrogen (DK)	HyProvide A60	60	0.25	30	4.2	72	15–100
ErreDue[l] (IT)	G256[m]	21	0.11	30	(5.4)	(56)	20–100
Hydrogenics[n](CA)	HySTAT-100–10[o]	15	0.08	10(25)	(5.2)	(58)	40–100
Sagim (FR)	M 5000	5	0.03	7	(5)	(60)	n.a.
Linde AG (DE)	HYDROSS	n.a.[p]	n.a.	25	n.a.	n.a.	25–100
PEM electrolysis (PEMEL)			MW				
Giner Inc. (US)	Allagash[q]	400	2	40	5	60	n.a.
Hydrogenics[n](CA)	HyLYZER – 3000[r]	300	1.5	30	(5–5.4)	(56–60)	1–100
Siemens (DE)	SILYZER 200	225	1.25	35	(5.1–5.4)	(56–69)	0–160
ITM Power (GB)		127[s]	0.7	20–80	(5.5)	(54)	n.a.
Proton OnSite (US)	M400[t]	50	0.25	30	5	60	0–100
AREVA H2Gen[u] (FR)	E120[v]	30	0.13	35	4.4	68	10–150
H-TEC (DE)	ELS450	14.1	0.06	30/50	4.5	67	n.a.
Treadwell Corp. (US)		10.2	n.a.	76	n.a.	n.a.	n.a.
Angstrom Advanced (US)	HGH170000	10	0.06	4	(5.8)	(52)	n.a.
Kobelco Eco-Solutions (JP)	SH/SL60D[w]	10	0.06	4–8	(5.5–6.5)	(46–55)	0–100
Sylatech (DE)	HE 32	2	0.01	30	4.9	61	n.a.
GreenHydrogen[x] (DK)	HyProvide P1	1	0.01	50	(5.5)	(55)	n.a.
Solid oxide electrolysis (SOEL)			**kW**				
Sunfire (DE)	RSOC	~0.6	2.2[y]	10	(3.7)	(96)	– 100 to 100[z]

[a] Entries in column 3, 4, 6 and 7 are partly our own calculations based on other relevant columns.
[b] Specific energy consumption of the stack, values for the overall system given by manufacturers are indicated in brackets.
[c] Efficiency calculation based on LHV of hydrogen (3 $kW h/Nm^3$), efficiency based on HHV of hydrogen (3.54 $kW h/Nm^3$) is 18% higher.
[d] ELB and IHT are based on the same technology.
[e] Electrolysis technology of PERIC distributed by Wasserelekctrolyse Hydrotechnik in Germany.
[f] NEL Hydrogen acquired GHW (DE), H2Logic (DK), Proton Onsite (US) and Rotolyzer (NO).
[g] "atm." means close to atmospheric pressure (20–40 mbar).
[h] Modules are supplied by Next Hydrogen Corporation (CA).
[i] 5.9 kWh/Nm^3 at nominal production rate of 450 Nm^3/h, 5.1 kWh/Nm^3 at 225 Nm^3/h.
[j] McPhy acquired Piel (IT) and Hytec Enertrag (DE) in 2013.
[k] ETOGAS offers systems with a hydrogen capacity of 250 Nm^3/h, 1.2 MW, consisting of 4 stacks.
[l] Modules of ErreDue are also sold by Pure Energy Centre (GB).
[m] ErreDue offers systems (G256) up to a hydrogen capacity of 171 Nm^3/h, 0.9 MW, consisting of 8 stacks, a doubling of the current stack capacity is in development.
[n] Hydrogenics acquired Stuart Energy (CA) which acquired Vandenborre Hydrogen Systems (BE) and Elwatec (DE).
[o] Hydrogencis offers the skid-mounted system HySTAT-100-10 with a hydrogen capacity of 100 Nm^3/h, 0.5 MW, consisting of 6 cell stacks.
[p] HYDROSS is offered with a hydrogen capacity up to 250 Nm^3/h, number of cell stack was not available.
[q] Giner is developing a stack with a rated hydrogen capacity of about 1100 Nm^3/h at 15.5 bar (Kennebec stack).
[r] Hydrogencis offers HyLYZER-3000-30 as an indoor installation with a hydrogen capacity of 3000 Nm^3/h, 15 MW, consisting of 10 cell stacks.
[s] ITM Power offers a platform with a capacity of 1365 kg/day (630 Nm^3/h), 3.5 MW, consisting of 5 stacks.
[t] Proton Onsite offers modular, skid-based systems up to 400 Nm^3/h (M400), 3 MW consisting of 8 cell stacks.
[u] AREVA H2Gen results from the fusion of AREVA Helion (FR) and CETH2 (FR) in 2014.
[v] AREVA H2Gen offers skid-mounted systems up to 120 Nm^3/h (E120), 0.6 MW, consisting of four stacks.
[w] Kobelco Eco-Solutions offers skid-mounted systems up to 60 Nm^3/h (SH/SL60D), 0.3 MW, consisting of six stacks.
[x] GreenHydrogen ApS and EWII Fuel Cells A/S (former IRD) have entered into a long-term partnership for the commercialisation of EWII Fuel Cells PEM electrolyser ELZE1050.
[y] Modules with a rated electrical power of 150 kW (40 Nm^3) are offered by Sunfire.
[z] Reversible operation of SOC in electrolysis and fuel cell mode possible, idle mode close to operation temperature possible.

Summarizing the technology status, it is possible to affirm that alkaline electrolysis (AEL) represents the most mature technology, with the lowest specific investment and maintenance costs. There are manufacturers able to supply AEL with single-stack capacities up to 6 MW. In contrast, the development of PEMEL has been driven very strongly by flexible energy storage application in recent years. PEMEL has entered the MW class and several pilot plants in the MW range up to 6 MW have recently been realised. PEMEL offers several advantages compared to AEL with regard to compact design (high current-densities), pressurised operation and flexibility. Investment costs are likely to fall in the future due to the higher volume production of electrolysers, supply chain development, improvements in manufacturing and technology innovations supporting the competitiveness of electrolysis against other storage options. In view of using this technology for storage and grid stabilising, both PEMEL and AEL systems offer very fast load dynamics (response<1 s). Differently from the latter, SOEL has the potential to increase the efficiency of hydrogen production and offers interesting features as reversible operation but the development of SOEL systems and the proof of lifetime, pressurised operation and cycling stability have to be confirmed. As will be discussed in the power-to-gas section, certainly in Germany, the trend is towards the installation of more PEM-type electrolysers (see **Figure *5***).

2.1.1.3 Artificial photosynthesis

There are other methods in addition to electrolysis using renewable electricity as noted above, from which so-called 'green' hydrogen can be obtained namely: (i) photo-catalysis (or photo-electrochemical water splitting (PEC)) and (ii) photo-biological water splitting. A considerable global initiative which is driven by the European Union called Mission Innovation, has also a specific solar challenge which aims to considerably progress solar fuels SotA through high level international cooperation (Mission Innovation, 2018).

Photo-catalysis or photo-electrochemical water splitting (PEC) is a process which splits water into hydrogen and oxygen, using the energy of absorbed light and semiconductor based photo-electro-chemically active materials (also called photo-catalysts). The photo-catalyst absorbs the light photon, transmits its energy and uses it to perform redox reactions in water. The photo-catalyst consists of a photo-anode and photo-cathode connected together. Depending on the design set-up, the produced gasses (hydrogen and oxygen) are collected from the same (mixture) or separated volumes (pure gasses). The reference method for PEC production of green hydrogen is the use of green electricity coupled to an electrolyser. In this way, PEC can be said to directly harvest sun energy and convert it into hydrogen. PEC technology is said to have shown considerable progress in the last 10-15 years; the solar-to-hydrogen conversion ratio for example, has grown from approximately from 3% to well above 10% (with a claim of 18.3%). However, the technology is still considered to be at the lower end of the TRL-scale, i.e. TRL 3. With regards to development trends in this area, the US' Department of Energy's Fuel Cell Technology Office state three areas in which this technology is being improved, (i) efficiencies are being improved through enhanced sunlight absorption and better surface catalysis, (ii) the durability and lifetime of systems are being improved with more rugged materials and protective surface coatings, and (iii) hydrogen production costs are being lowered through reduced materials and materials processing costs (US Dept. of Energy, 2020).

Figure 4. Schematic diagram of a photo-electrochemical cell (source: Ahmad et al, 2015)

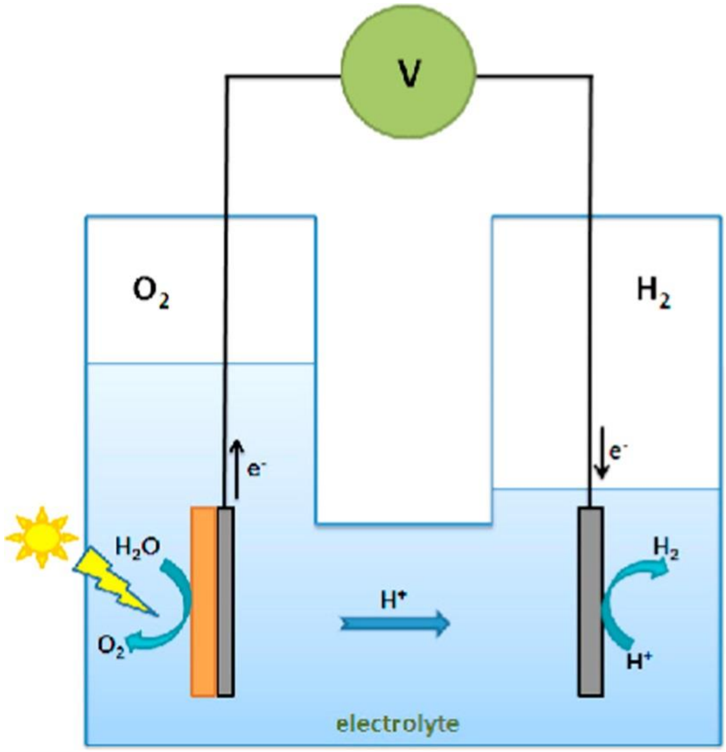


Photo-*biological* water splitting uses some bacteria and algae to produce hydrogen. This process makes use of cyanobacteria or unicellular green algae, which are able to absorb sun light and split water (also called photolysis). It relies on the same mechanisms involved in photosynthesis to fix CO_2 and the enzyme hydrogenase for converting protons into H_2. It can be also based on natural microbes, or by replacing living cells with a technology to mimic the biochemical reactions, and can be integrated into photo-catalysis devices to optimise hydrogen production.

2.1.1.4 H_2 as a fuel

Before moving to fuel synthesis (in which hydrogen is used to form fuels), a very brief introduction to the use of hydrogen as a fuel is made. Today hydrogen is chiefly used as a chemical feedstock or reducing agent in oil refineries, for biofuels production, and in the ammonia, methanol and metal industries. The hydrogen demand by these industries is typically met by natural gas reforming or coal gasification as these are the cheapest among the currently available production technologies.

As fuel in itself, hydrogen-powered fuel cell electric vehicles can be considered to be still at a very early stage of deployment but increasing, with the IEA reporting just over 1 400 vehicles on the road in Europe up to the end of 2018 (IEA, 2019). In addition to road vehicles, other surface transport applications have been proposed, for instance for trains (Alstom, 2018) and mining equipment (Electrek, 2020). The hydrogen plus fuel solution proposes a way to help 'green' the heavy transport sector and offers some advantages compared to battery-equipped machines: the possibility to operate the fleet for a whole day, refuelling during night-time, and low *expected* cost of H_2 (when produced to cut the peak of RES production). In spite of these strong advantages, the direct use of H_2 does have some drawbacks: safety risks, the need to create a widespread dedicated supply chain, etc. For aviation, hydrogen's low energy density precludes it for the time being.

A considerable number of pilot and demo initiatives exist which it is hoped will begin to improve the levels of penetration of H_2 as a fuel compared with other alternative fuels. For a more full picture of the work in the direct usage of H_2 as a fuel, and in hydrogen and fuel cells technologies for transport and stationary applications, interested parties are directed to the Fuel Cells and Hydrogen LCEO TDR (as referred to previously), and also to the European 'Fuel Cells and Hydrogen Joint Undertaking' initiative[4].

Alternatively, if H_2 can be produced at low cost using renewable energy, a route is opened to e-fuels (as discussed in more detail in the following sections) that do not require any other modification to the infrastructure nor to the rolling stock, but are energetically heavy to produce.

2.1.2 CO_2 capture and utilization

The topic of carbon capture for re-use (or storage) is fully detailed in another LCEO TDR 'Carbon Capture, Utilisation and Storage (CCUS)' (LCEO TDR, 2018). Therefore, the main points from this report have been briefly summarised here, and complimented with a recent literature review. In addition, the JRC has recently carried out extensive LCA work on fuels which require carbon capture, for possible use in future legislation, and some of this research has been also used to build this section.

- High concentration CO_2 waste stream capture;
- Amine-based post combustion capture;
- Other capture technologies.

2.1.2.1 Waste high concentration CO_2 from renewable sources

Large stationary sources of emissions from industry are widely distributed throughout the world. The four main carbon emitting industries, responsible for a majority of industrial CO_2 emissions are: the iron and steel industry, the cement industry, petroleum refining and the pulp and paper industry (Leeson et al, 2017). Of these, the authors found that the cement sector is likely to be able to capture the highest proportion of emissions due to the simplicity of the process and the single flue stream (Leeson et al, 2017). Certainly, the cement industry is one of the largest industrial emission sources of CO_2, contributing approx. 5% of global anthropogenic CO_2 emissions. State of the art cement plants emit 60% of their total CO_2 from calcination of the $CaCO_3$ containing raw material, while 40% come from the supply of heat for the process. This large share of CO_2 from calcination limits the effect of efficiency improvements from the fuel combustion side, and makes CO_2 capture technologies especially useful to reduce a cement plant's CO_2 emissions (Hornberger et al, 2017).

Given the relevance and suitability of the industry towards CO_2 capture, Hornberger et al (2017) further showed in a project funded under Horizon 2020 called CEMCAP, testing at a 200 kW_{th} pilot plant scale (considered to be TRL 6) proved successful, and high CO_2 capture rates (even above 95%) were been achieved over a wide range of operating conditions. More recently it was announced that advanced plans are underway to make a plant in Norway the world's first zero carbon emissions cement plant (Euractiv, 2019).

2.1.2.2 Amine-based post combustion capture

Post-combustion capture (PCC) is regarded as the most feasible, near-term technology to significantly reduce CO_2 emissions from existing coal-fired power plants, due to the following potential benefits (Yu, 2018).

PCC technologies can use adsorbents, absorbents, membrane, chemical looping and cryogenic processes. The most advanced, near-term technologies use amine-based solvents or solvents that contain amino groups such as ammonia and amino-acid salts.

[4] https://www.fch.europa.eu/page/who-we-are

Some technologies have been installed commercially in coal-fired power stations, including the Boundary Dam and WA Parish power plants in Canada and Texas respectively (Yu, 2018). For more detail on the state of the art of the principal individual developments in post combustion capture, please see Table 6 in the Annex.

2.1.2.3 Other capture technologies

As already presented, there are several technologies to capture CO_2 but only amine has been discussed, as it is widely recognised as a particularly promising technology linked to alternative fuel production. Nevertheless if more detail is required on the subject, a wider description of the state of the art of the other technologies is available in paragraph 2.2.2 of the LCEO TDR D2.2.9 'Technology development report on Carbon Capture Utilisation and Storage (CCUS).

2.1.3 Fuel synthesis: Power-to-Gas

Power to Gas technology (not considering pure hydrogen injection into the natural gas grid) is based on the methanation reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

There are three main pathways to obtain methanation from H_2 and CO_2: biological methanation, isothermal catalytic methanation and the adiabatic fixed-bed methanation.

Biological methanation is suitable for small power plants as waste heat can be used to supply the process. CO_2 is used as the feedstock for microorganisms. The main advantage of the biological pathway is that it is highly tolerant to impurities: some of the minor disruptive components such as sulphur and oxygen can be partly removed during biological methanation. Therefore, the cleaning process of feed gas can be simplified. Biological methanation remains in the laboratory and demonstration stage (Sterner et al., 2014). For very large scale (exceeding 100 MW), the adiabatic fixed-bed methanation method is the most effective type of plant and it has already entered commercial production (Shaaf et al., 2014).

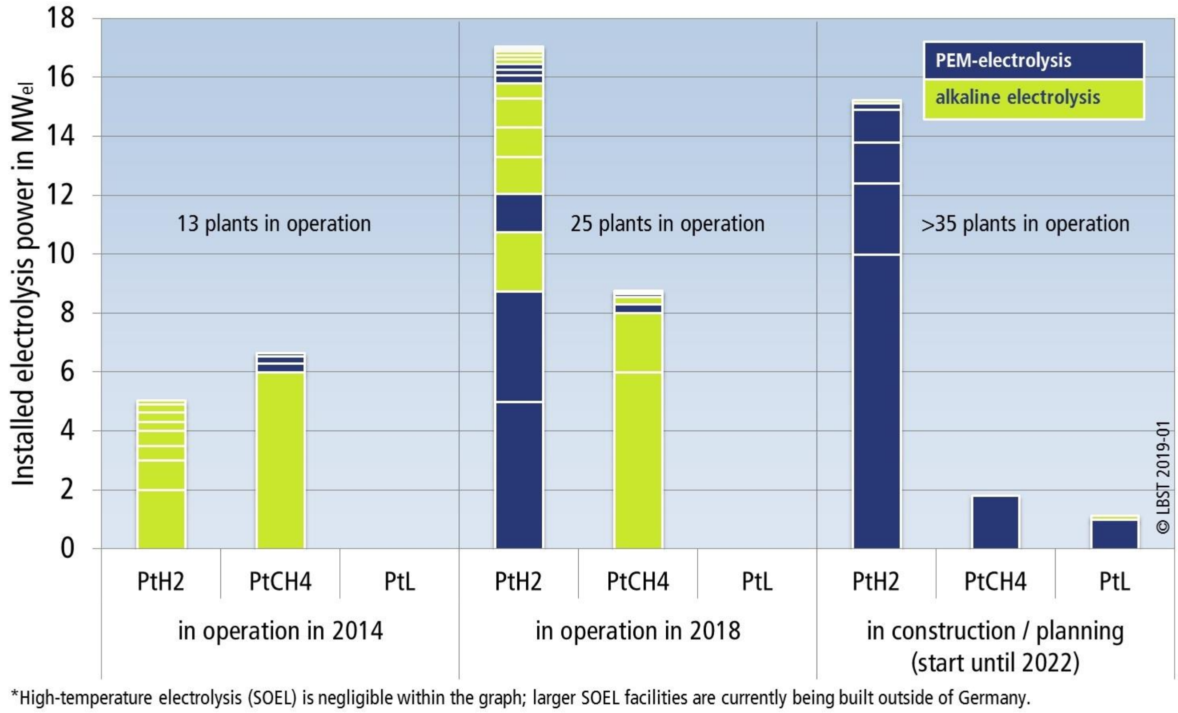
The isothermal catalytic methanation method, including three- phase methanation and fluidized-bed reactors, is typically considered as the most suitable pathway for regular plant sizes (Ma et al., 2018). However, this technology is still in the experimental phase and is undergoing large-scale testing (Gotz et al, 2016).

The main advantage of a PtG plant is today related to the possibility to act as storage for fluctuating RES. Recent developments in Germany indicate at least in that country, there is a notable growth in PtG (both in operation or planned) of more than a tenfold increase within one year; principally in power to hydrogen but also in power to methane projects (TÜV SÜD, 2020). The high level of interest in Germany in this technology is further confirmed by Thema et al (2019) who also note Denmark have a growing number of projects.

PtG is to be seen as an option to deal with power surpluses rather than a technology to satisfy the current gas demand in a sustainable way. The reason for this is its low efficiency and relative sizes of the electricity and gas sectors. The energy efficiency of the entire PtG conversion chain from renewable energy to gas and then to electricity can reach 30–40% which is equivalent to that of conventional thermal power plants, and this value is expected to reach 40–50% by 2030 (Sauer, 2012).

Due to the high technology cost, one option for PtG is to increase the size of the facilities to benefit from economies of scale. On the other hand, the amount of power needed for such plants places uncertainty over the fact that plants will only operate with power surplus from RES. A further complication can be the CO_2 sources (in the required quantities and location) which will directly affect the overall system performance. However, PtG has the main advantage of being able to produce different compounds and for different sectors; this gives more robustness to the technology as it provides more revenue streams.

Figure 5. Development of PtX capacities in Germany (Source: LBST, 2019)



2.1.4 Fuel synthesis: Power-to-Liquid

The main constituents of PtL are electricity, water and carbon dioxide (CO_2). The generic PtL production process consists of hydrogen production in an electrolyser, using renewable electricity and water as feedstock; then, hydrogen and CO_2/CO are synthesized to form hydrocarbons. The generic PtL terms is used to refer to two main pathways: the Fischer-Tropsch (FT) pathway and the methanol pathway.

The literature review reveals significant differences among the studies, resulting in a broad range of electrofuel production cost estimates, 10–3500 EUR2015/MWh (Brynolf et al., 2018). According to Cerulogy (2017), production costs in the near term are likely to be EUR 3 000/ton for electrodiesel (or electrojet or electropetrol), possiblly reducing to EUR 1 200/ton for a scenario with electricity cost of 5 cEUR/kWh and a facility with 50% conversion efficiency.

2.1.4.1 Fischer-Tropsch

FT synthesis, originally designed to produce liquid fuels from coal, uses syngas (a mixture of hydrogen and carbon monoxide) to produce liquid hydrocarbon fuels. The syngas can be generated from virtually any carbonaceous feedstock (Schmidt et al, 2018). Large scale FT plants using coal or natural gas feedstocks are running successfully.

The Fischer-Tropsch synthesis theoretically can produce a variety of hydrocarbons, including gasoline and diesel:

$$2H_2(g) + CO(g) \rightarrow -CH_2 - (l) + H_2O(g) + 165\ kJ(at\ 400K),$$

where $-CH_2-$ is part of a hydrocarbon chain.

The relevance of FT synthesis for PtL is based on the fact that syngas can be generated from virtually any carbonaceous feedstock. Apart from coal, this includes methane (natural gas, flare gas or biogas from fermentation) in the gas-to-liquids (GtL) pathway as well as dry biomass, but also syngas electrochemically generated from CO_2 and water, as in the case of PtL.

Although FT synthesis has a long history of industrial application, new production pathways give rise to new developments in FT technology. The main difference between the conventional FT processes and new enterprises is scale, as the trend is to reduce the average plant size to match different and more widespread sources of CO_2.

Microstructured reactor designs allow increased surface areas in relation to the reactor volume, strongly enhancing heat transfer and improving temperature control. Examples of companies driving the commercialization of microchannel FT technology are Velocys Inc. and Ineratec GmbH.

According to a review of literature, the investment costs for FT liquids are defined as being in the range – with a considerable spread - of EUR 300–2100/kW fuel, for different plant sizes (Brynolf et al., 2018).

2.1.4.2 Methanol route

An alternative to FT synthesis for producing liquid fuel is related to the production of methanol, to be used as an intermediate product (although a minor percentage of methanol is allowed in the EN228 European road gasoline fuel standard). Today methanol is produced at industrial scale from synthesis gas, typically generated from natural gas or coal, using catalysts (typically the ternary Cu-ZnO-Al_2O_3). Methanol is also of importance in the production of transport fuels, such as methyl ethers (e.g. DME); or as marine fuel.

$$CO + 2H_2 \rightarrow H_3COH$$

The reaction needs CO and but is boosted by the presence of small quantities of CO_2 (about 10% in the feed stream (Martin, 2016).

Current research focusses on the development of processes supporting direct hydrogenation of CO_2, without requiring prior reaction to generate CO. The direct conversion of CO_2 poses several technical challenges, particularly with respect to required pressures (higher than 30 MPa) (Schmidt et al, 2018).

An interesting option for road and aviation transport sectors is the possibility to convert methanol into liquid hydrocarbons. In addition to the more commonly known methanol-to-gasoline (MtG) process that is currently deployed in several commercial plants, the route has also demonstrated the conversion of methanol into middle distillate (diesel and kerosene), with a yield up to 80% (Schmidt et al, 2018). The investment costs for methanol synthesis have been estimated at EUR 200–1200/kW fuel in the literature, for different plant sizes. As noted in the FT section above, the range is again considerable.

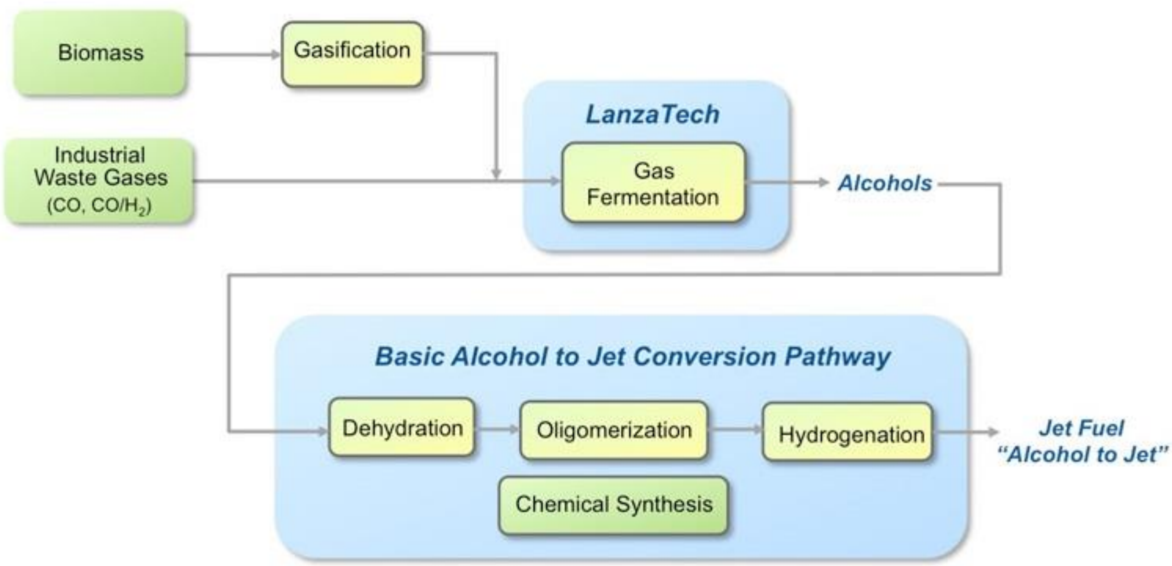
2.2 Microbial fermentation

Principally promoted by or certainly publically associated with the Lanzatech Company, this process involves biological conversion of carbon to product alcohols through fermentation of residual gases. These engineered microorganisms are able to grow on gases (rather than sugars, as in traditional fermentation) and carbon-rich off-gases, using them as source of carbon. This technology provides a novel approach to carbon capture and reuse (Lanzatech, 2018).

2.2.1 Industrial off-gases processed by bacteria into ethanol

As introduced, the process (most currently identified with Lanzatech) can use industrial off-gases (such as from the steel industry, and oil refineries) to produce liquid commodities. Lanzatech use proprietary microorganisms to feed on the gases and make alcohols. The alcohols obtained from fermentation can be further refined for producing fuels, such as alternative aviation fuels (Figure 6).

Figure 6: General process flow gas to jet (source: GCG, 2016)



The technology appears to be advancing to large demo stage. Towards the end of 2019 it was reported that Lanzatech in a joint operation with a steel company in China, had in its first 12 months of operation produced 27 000 tonnes of ethanol. There is also interest in further processing the ethanol to jet fuel. In 2018 the world's first test flight using fuel made via microbial fermentation was announced by Virgin Atlantic, partners of Lanzatech since 2011 (Virgin, 2018). Virgin also disclosed Lanzatech had successfully produced 12 tonnes of jet fuel derived from their ethanol (Virgin, 2018a).

The key issue from a GHG saving point of view would be to consider the existing use if any of the gases required as feedstock for this process. Simply defining them as waste – wastes under the RED have typically received a zero GHG emission intensity until their point of collection - may not reflect the current uses of these streams in industry. For instance they can be widely used for energy recovery in CHP plants.

2.2.2 Mixture of sewage gas & natural gas processed by bacteria into ethanol

A similar process to the above, but first involves a step coupling together sewage gas and natural gas by using a concentrated plasma to create syngas. Following this, a gas fermentation technology step similar to that in the previous point is used to make ethanol. This chain appears to relate to a single firm with little recent information, therefore it is not considered in detail. Although the authors note there is research into using plasma to create syngas from glycerol from biodiesel production (Tamošiūnas et al, 2019). Strictly speaking this would result in a biofuel or bio-syngas and would therefore be outside the scope of the advanced alternative fuels considered in this report.

2.3 Other possible unconventional fuel production pathways

Other alternative pathways may be worth a brief description, in view of making a more comprehensive description of the alternatives to current fuel production technologies. In particular, ammonia can be produced from renewable H_2 by a cyanobacteria-based process, resulting in an interesting fuel for the road sector. A second option, using a waste stream such as plastic, is also considered for liquid fuels production, with a potential to lower GHG emissions in the transport sector. The authors note there is an **Unconventional Fossil Fuels** LCEO TDR, however this is primarily concerned with fuels from hydraulic fracturing (or fracking), and while their production process differs from traditional fossil fuel production methods, the end products are the same.

2.3.1 Ammonia brief description

While hydrogen is a possible enabler of a low carbon economy, it faces (amongst others), issues around its storage and distribution. Indirect storage media such as ammonia (or indeed methanol) are other options, as are their possible direct use as fuel. Ammonia is carbon free and has an established and flexible transportation network, and it is seen by some researchers as possibly providing a next generation system for energy transportation, storage and use (Valera-Medina et al, 2018). In January of 2020, it was announced that MAN Energy Solutions and other significant partners would join to develop an ammonia fuelled tanker ship, noting that the shipping industry see ammonia as one of the pathways towards zero-carbon emitting vessels (Lloyds Register, 2020).

Indeed ammonia can be seen as having favourable properties for use as an automotive fuel, namely good storage properties and its mature production and distribution infrastructure. However, the sustainability of ammonia is questionable due to the environmental impact from conventional production technology, and the need for a secondary hydrocarbon fuel to promote combustion when used in internal combustion engines. Care would have to be applied with respect to its handling, as it is caustic, flammable and hazardous in concentrated form, and as a gas can explode when heated. Researchers conducting a life cycle analysis of an ammonia-fuel system, found the most significant parameter was end-user vehicle fuel economy - they therefore recommended improving vehicle technology to enable the use of ammonia (Angeles et al, 2018). With regards to an alternative method of producing the ammonia, the researchers found a cyanobacteria-based process was optimal (Angeles et al, 2018).

2.3.2 Fuel from waste plastics pyrolysis/gasification

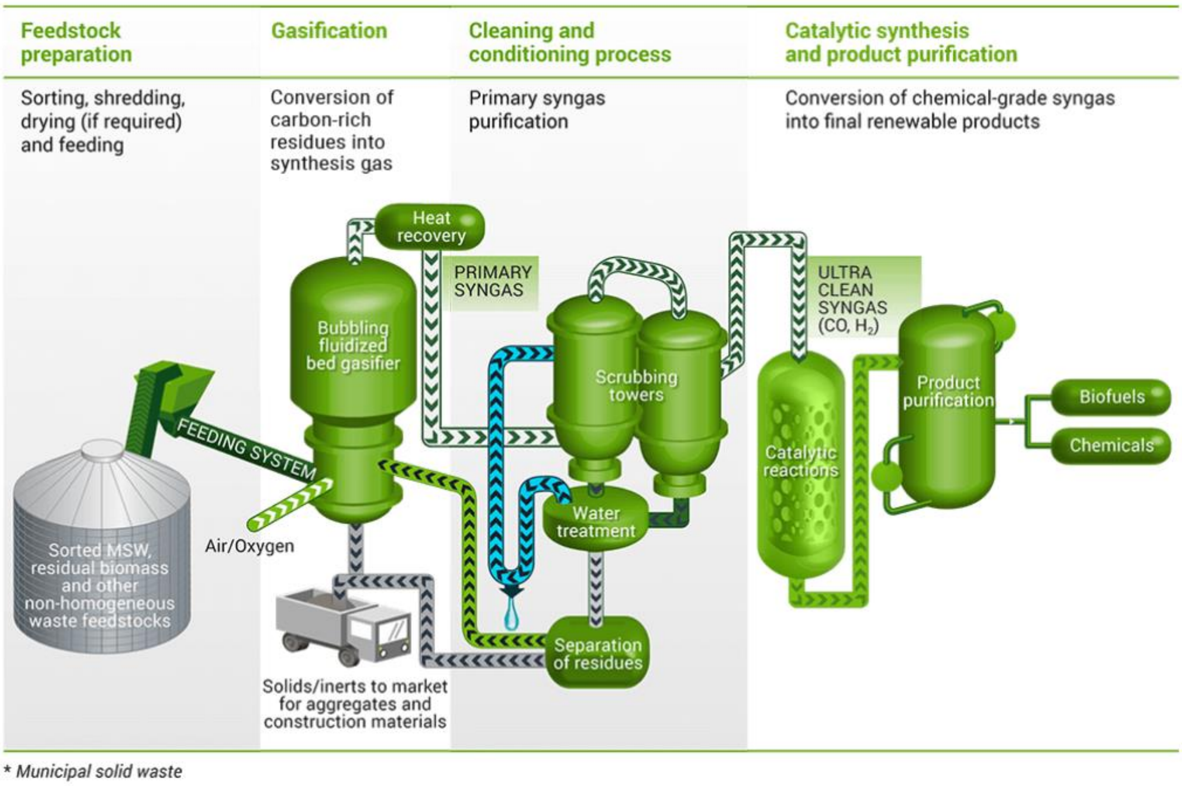
Synthesis of liquid fuels from waste is another promising pathway for reducing the carbon footprint of the transportation industry (and helps progress waste management towards zero landfilling).

Two main thermochemical processes can be used: gasification + FT and pyrolysis. Both these technologies have been widely described in *Deliverable D2.2.12 for the Low Carbon Energy Observatory: TDR Sustainable Advanced Biofuels-2018* for biomass feedstock. Indeed the use of sorted MSW (or Refuse-derived *fuel* (RDF)), basically constituting plastics, poses different technological challenges to these technologies.

Demo scale plants exist that pyrolyse plastics from post-consumer recycled materials, and directly mine feedstock from old landfills without any pre-treatment. The pyrolysis oil, consisting of over 95% hydrocarbons within the gasoline and diesel ranges, can be upgraded to transportation fuels in existing refineries.

Enerkem is a commercial scale process able to convert solid wastes into methanol, ethanol or other renewable chemicals. The methanol is considered not only as a possible fuel, but also as a chemical building block for the production of secondary chemicals, such as olefins, acrylic acid, n-Propanol, and n-Butanol.

Figure 7: ENERKEM process scheme (source: https://enerkem.com)



Velocys plc (VLS.L) is another example of the renewable fuels company active in the field of MSW to fuel technologies. In particular Velocys is a technology provider for FT medium-to small scale reactors. Velocysis provided their reactor to the ENVIA plant (https://www.enviaenergy.com/) but recently the Board of ENVIA Energy has decided to suspend operations at the Oklahoma City plant and undertake a review of strategic alternatives in order to preserve the value inherent in the facility. More recently Fulcrum BioEnergy (http://fulcrum-bioenergy.com) started construction for Phase 2 of its first waste-to-fuels project, the Sierra BioFuels Plant in Nevada.

It worth noting that these plastics are more likely to be from fossil origin, and so may not be considered renewable, or at best, only partially renewable. In the framework of the aviation industry's ICAO-CORSIA activities, for the definition of Core LCA default values for alternative aviation fuels, the Alternative Fuel Task Force proposed an integrated methodology for defining credit for plants able to divert MSW from landfilling. The methodology allows the calculation of GHG emissions on the basis of the biological carbon content in the sorted MSW, plus credits for the biogas avoided emission from landfill and additional recycled materials associated with the fuel production (source: www.icao.int/environmental-protection/CORSIA/Pages/default.aspx).

3 R&D Overview

3.1 Overview of H2020 projects

The following provides an overview of the projects now running and funded under the Horizon 2020 program. Many projects noted in this chapter have multiple areas of interest, and as such, their classification could fall into more than one category. The approach taken was to group projects based on their likely main focus. So while a piece of work may be considered within the 'projects using CO_2' section, it could also include elements related to H_2. The projects include fuel synthesis as an aim, or at least claim to have possible applications in fuel production (i.e. the preference was to cover projects which are not pure H_2 projects or which are principally linked to the use of H_2 itself as a fuel which are outside the scope of this report). In other initiatives such as KIC-Innoenergy, projects for fuels appear to be focussed on bio-based systems, while InnovFin do not appear to have advanced renewable fuel specific projects currently.

Due to the relatively new nature of most of the pathways, we note a low TRL can be seen in many projects, nonetheless the advances gathered by such research, are aimed to impact production pathways at higher TRL, making them more efficient (from an energetic or carbon-saving point of view), or indeed furthering the possible feedstock bases for fuel production.

- The H2020 projects can thus be broadly categorised into those primarily focussed on **H_2 generation, through the use of electrolysis or water-splitting** processes. The focus is on fuel production linked schemes, so there is often a synthesis step, whereby the obtained hydrogen is combined with carbon (such as from CO_2) to make fuels. A total of four H2020 projects were identified as belonging to this category. As noted, the wider area of hydrogen R&D, i.e. those projects *not focussed on or including further fuel synthesis work* is considerable, and readers wishing to see a more complete H_2 R&D picture are kindly directed to both the LECO TDR D2.1.13 and the EU's FCH JU.
- The second broad category of research projects has been those more aimed at improving the **use of carbon dioxide, or other carbon containing gases** as a feedstock for subsequent fuel production. Successful use of CO_2 as a feedstock could have significant impacts on GHG balances of fuel production pathways, certainly compared to traditional methods. A total of seven H2020 projects were identified as belonging to this category.
- A third category, which we define as various, **contains other projects** which either do not simply fit into either of the above categories, or conversely, appear to sit evenly between both categories. By that, it is meant that some fuel production research projects consider both H_2 production and CO_2 capture and use with equal priority. A total of four H2020 projects were identified as belonging to this category.

With regards to EU funding, a total amount of almost EUR 62 million was observed to have been awarded to the projects. Projects focussed principally on using carbon containing gases, or CO_2 as a feedstock, were awarded 37% of grants, or EUR 22.7 million. Projects mainly on H_2 production, electrolysis or water-splitting received EUR 30.4 million, or 49% of the total funding. While approximately 14% of funds (amounting to EUR 8.9 million) was awarded to projects engaged in both the above categories, or in research in other projects (please see also Figure 8).

As previously mentioned in the report, the number of projects in this area is relatively small, with one or two projects generally running per MS, in the group of MS active in H2020 projects in this area. The exception is in Germany, where 5 projects are active. It is not surprising then that Germany is seen as having been awarded the most amount of funding, followed by Belgium, Spain and Italy respectively (please see Figure ***9***).

Figure 8. Breakdown of H2020 funding by technology group to advanced alternative fuel projects

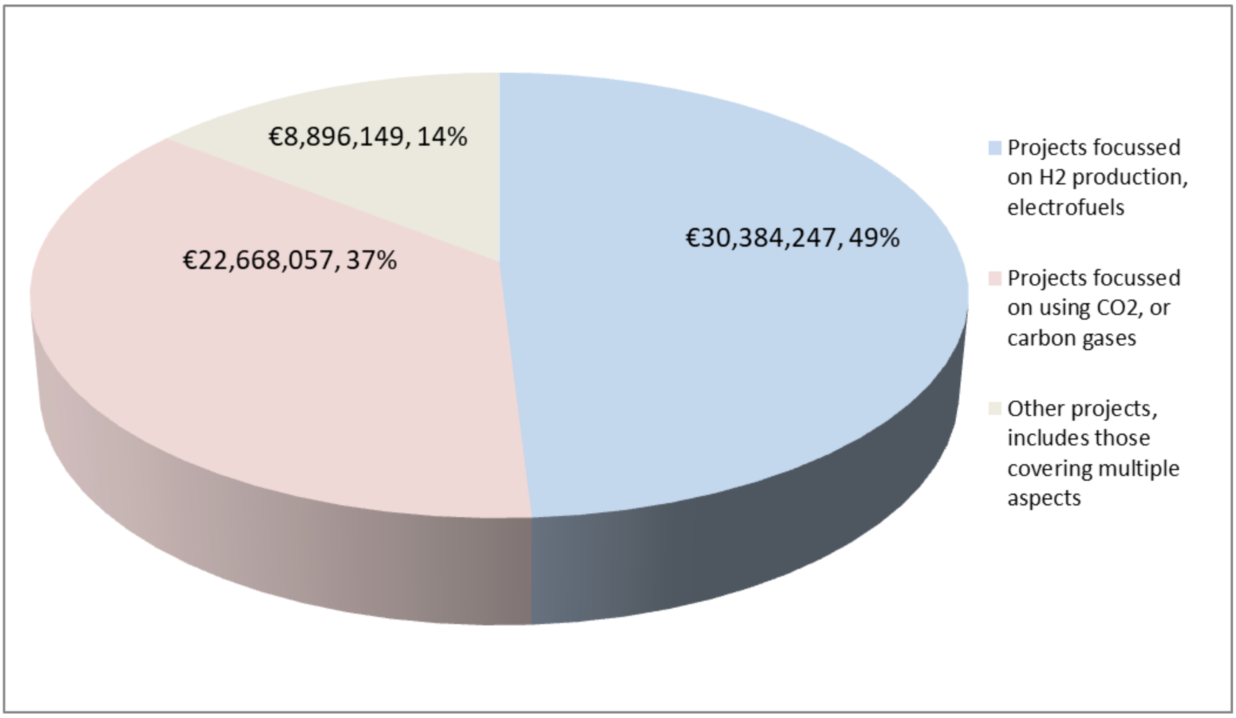
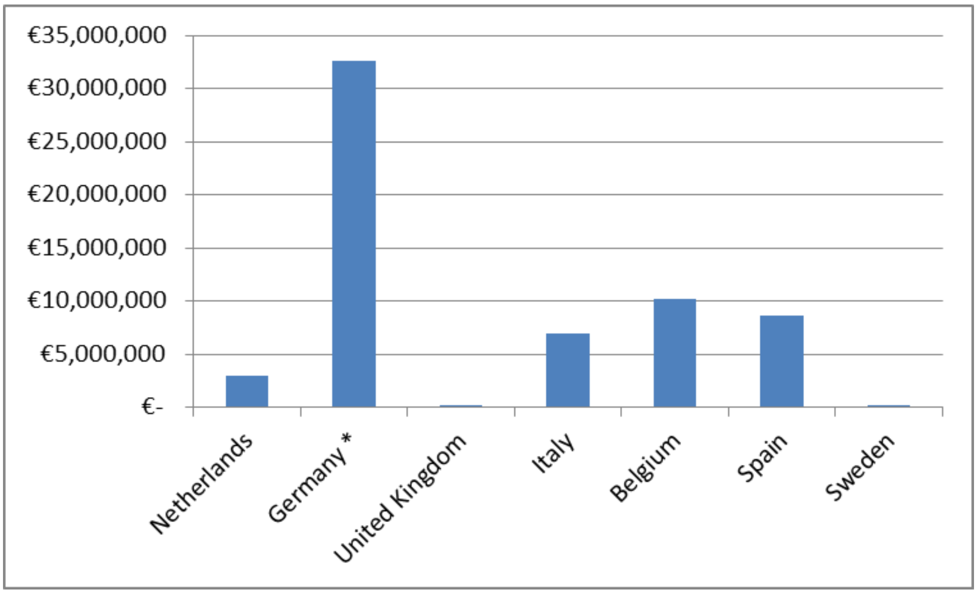


Figure 9. Breakdown of H2020 funding by Member State to advanced alternative fuel projects



3.2 SET-Plan flagship projects in this area

Certain SET-Plan 'flagship projects/activities' as provided by the Temporary Working Group (TWG) on the 'Implementation Plan for the SET-Plan Action 8 on Bioenergy and Renewable Fuels for Sustainable Transport' are included briefly in the following section. The authors note these projects generally focus on the production or direct use of H_2 as a fuel, ultimately for transport purposes. Indeed only the 'Balance' project mentions a further fuel synthesis part specifically, reflecting the comparatively emerging nature of interest in this field.

Project "CO_2-free logistics", Linz, Austria

The project "CO_2-free logistics" is based on the idea to reduce emissions in the freight transportation sector, by using hydrogen as a fuel. Hydrogen will be produced by an electrolyser, which is operated using renewable energy sources. Partners: DB/Schenker, Fronius, HyCentA, Energieinstitut an der JKU.

Balance (EU-ECRIA)

Aims at aiding increasing penetration of renewable power, alternative fuels and grid flexibility by cross-vector electrochemical processes using Reversible SOC. Partners: VTT FIN, coordinator DTU, DK; CEA, F; ENEA, IT; TU Delft, NL; University Birmingham, UK; IEN, PL; EPFL, CH; liaises with IEA, IEC, Sunfire (DE company), FZ Juelich.

H2Future/Steel plant of voestalpine in Linz

A large-scale 6 MW PEM electrolysis system has successfully been installed and is operating at the voestalpine Linz steel plant in Austria. Hydrogen is produced using electricity from wind and hydro-power and the gas is being fed into the local gas network. Electricity grid services may be provided when producing hydrogen. The long term view is to use Hydrogen in the steel industry for direct iron ore reduction, slashing CO_2 emissions from the steel industry by 90%. Partners: Verbund Voestalpine, Siemens, ECN.

DEMO4GRID/Food Industry of MPreis Innsbruck, Austria

A large-scale 4 MW pressurised (33 bar) alkaline electrolyser will be installed and operated at the Mpreis food industry in Innsbruck, Austria. Hydrogen will be produced using electricity from hydro-power and be burned in a suitably modified boiler (special combustor) for heating oil, displacing NG. At a second stage this green hydrogen will be provided to fuel hydrogen fuel cells busses, as planned by the local community. Partners: IHT, Diadikasia, Mpreis, FHA, Inycom, fensystems.

3.3 Focus of national and international projects

Given the relatively small number of research projects identified as belonging to the area of advanced alternative fuels, there was a similar trend seen in MS, where projects were not numerous. The following section summarises the projects found of relevance, beginning with MS work followed by work occurring in other significant areas of the world.

There does not yet appear to be combined, or coherent international programmes specifically designed for the purposes of developing advanced alternative fuels. The JRC are participants in the IEA's Bioenergy Task 39 (on biofuels), and it appears they (or another Task) will likely begin considering some advanced alternative fuels in more detail in their coming triennium period of work. It will be therefore useful to see how this new work progresses.

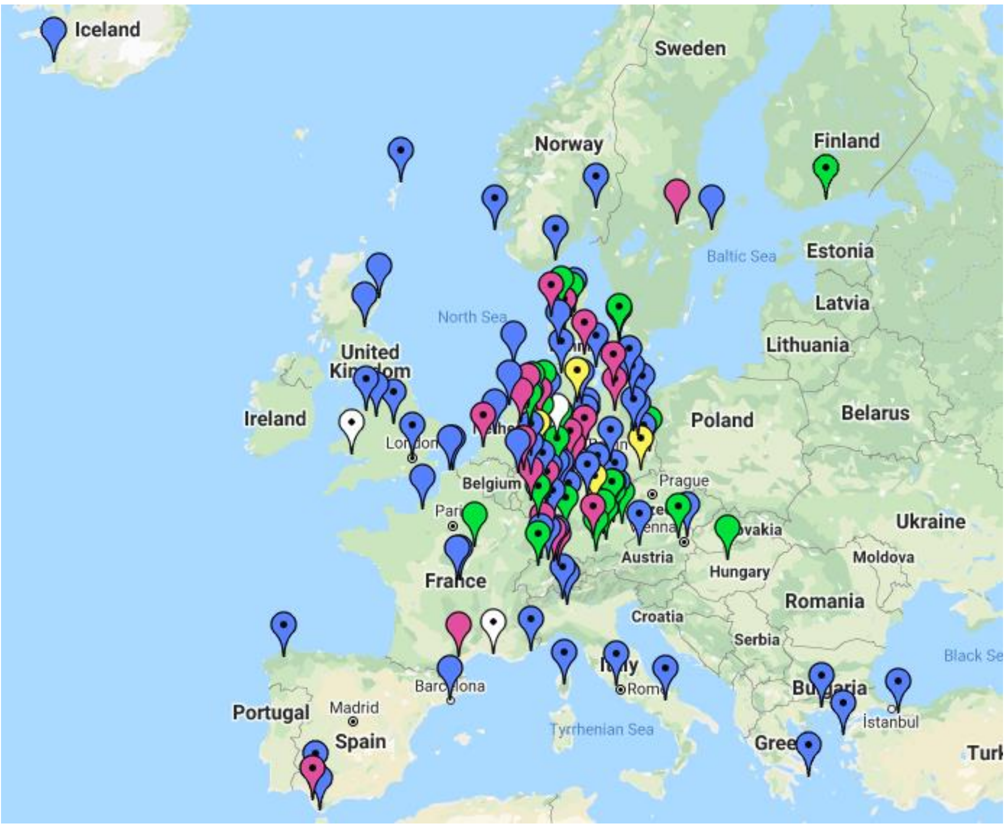
3.3.1 Europe

In **Germany**, ETOGAS (on behalf of Audi AG, in a project partly-funded by the German Ministry of Education) has invested in a 6 MW plant in Germany, which uses renewable electricity from wind power and CO_2 from a nearby biogas processing plant to produce e-methane (ETOGAS). Indeed multiple (principally power to gas) projects are coming online and more are planned in Germany – an overview of these is provided by TÜV SÜD (2020) and Thema et al (2019). In addition, Siemens and Evonik announced in late 2019 continued work on a joint project to develop a technically feasible basis for artificial photosynthesis (Evonik, 2019).

Carbon Recycling International (CRI) in **Iceland**, is producing methanol by using geothermal energy and CO_2 from the same source. A commercial plant has been operated by CRI since the end of 2011 with a capacity to produce 5 million litres of methanol per year (Carbon Recycling International, 2014). They are set to receive further funding to aid development from the Nordic Environment Finance Corporation (Carbon Recycling, 2018). The overall objective of the BioCat Project is to design, engineer, construct and test a commercial-scale power-to-gas facility at a wastewater treatment plant in **Denmark** and demonstrate its capability to provide energy storage services to the Danish energy system. The project is funded by EUDP, and the consortium consists of 7 companies from 3 different countries (BioCat website). Although strictly speaking outside the scope of this report, at the end of 2019 Denmark's own EUDP fund allotted just over EUR 4.6 million to Ørsted (formerly DONG Energy) and multiple partners to produce renewable hydrogen for direct use in road vehicles.

In **Sweden**, their Energy Agency funded a project titled "The role of electrofuels: a cost-effective solution for future transport?" aiming at the assessment of the potential of the electrofuels production in Sweden. This work led to a publication (Hansson et al., 2017). In **Norway**, a new project "E-Fuel 1" proposes to be the world's first commercial Power-to-Liquid jet fuel plant situated at Herøya, in Norway (Nordic Blue Crude, 2020). In the **Netherlands**, renewable hydrogen obtained using wind energy is planned to be used to hydrotreat waste oils and fats to produce fuels (Skynrg, 2019).

Figure 10 Overview of Power to X plants in Europe (source: Thema et al, 2019*)



* Note: an interactive and expanded version of the map, showing individual details on the plants is available in the online version of Thema et al (2019).

3.3.2 United States

Regarding electrofuels, in the US, ARPA-E U.S. government agency currently fund research on electrofuels. They have a slightly different description of what constitutes an electrofuel, and their program is using microorganisms to create liquid transportation fuels in a new and different way that they say could be up to 10 times more energy efficient than current biofuel production methods, with a focus on photosynthesis. They say most biofuels are produced from plant material that is created through photosynthesis, converting solar energy into stored chemical energy in plants. But they say photosynthesis can be considered inefficient, while the energy stored in plant material can require significant processing to produce biofuels.

Their electrofuels bypass photosynthesis by using *microorganisms* that are self-reliant and don't need solar energy to grow or produce biofuels (although they say these microorganisms can directly use energy from electricity and chemical compounds like hydrogen to produce liquid fuels from CO_2). Because these microorganisms can directly use these energy sources, the overall efficiency of the fuel-creation process is said to be higher than current biofuel production methods that rely on the more passive photosynthesis process. ARPA-E note their scientists can also genetically modify the microorganisms to further improve the efficiency of energy conversion to liquid fuels. And, because electrofuels don't use photosynthesis, they don't require prime agricultural land or water resources of current biofuels (ARPA-E, 2018).

For other technologies, the gas fermentation technology is principally being driven by one company, and thus R&D information appears to be scant. At time of writing it appears Lanzatech may be awarded funding by the US' DOE for further developing the alcohol-to-jet step of their process – so not strictly speaking for microbial fermentation it seems (Biofuels International, 2019).

For photo-electrochemical water splitting (PEC) (looking at hydrogen production, and thus not strictly aimed at liquid fuel production), two principle research centres are running, namely the Joint Centre for Artificial Photosynthesis (JCAP) at Caltech, and the Nocera Laboratory at Harvard. In February of 2020, the US Department of Energy (DOE) announced plans to provide up to USD 100 million over a five year period to fund research on artificial photosynthesis for the production of fuels from sunlight (DOE, 2020).

3.3.3 China

Finding clear information on progress in this area in China, is complicated somewhat by news being announced primarily in Chinese. Considering one of the main feedstocks for electrofuels – hydrogen – China is the world's largest hydrogen producer, so interest in renewable hydrogen production may grow. However, China mainly uses coal as a feedstock and they have disclosed that after pressurisation and storage, production costs for hydrogen remains three times less than hydrogen production via water electrolysis (Brasington, 2019), indicating the electrolysis route may not be a priority.

In the area of off-gas fermentation (i.e. carbon containing gas recycling), LanzaTech and partners (the state-owned Shougang Group), announced the start-up of the world's first *commercial* facility to convert industrial emissions to ethanol. The facility is at a steel mill in Hebei Province, and began operations on May 3rd of 2018 (Lanzatech, 2018a). This is in effect a part Chinese-state funded, first-of-a-kind facility with an annual capacity of 46 000 tonnes China is also engaged in artificial photosynthesis (water splitting) research, with joint research currently running between the East China University of Science and Technology and University College of London in this area.

4 Impact assessment

This section deals with providing an analysis of the main objectives and expected results of H2020 projects in terms of TRL. An overview of the national and projects identified as SET-Plan flagship projects was provided in the previous section. The overall goal is to assess the most relevant projects for each technology, and to highlight how the selected projects contributed or are going to contribute to improve the development of a certain technology.

The indicators considered were: improvement in TRL, expanded feedstocks, improved fuel production step, GHG emissions savings and improving market penetration. It should be noted that the analysis reports the objectives and results (if available) as they are presented by the projects partners; the calculations were not independently verified or endorsed by the JRC. Compared to the previous version of this report, the majority of projects analysed were still on-going although any new progress reports which had become available were analysed. The exception to this were two projects which have reached completion; one does not (at time of writing) have any final or concluding reports available on CORDIS. The other concluded project did however have quite a full array of reports, and it was found that a pilot plant was built and successfully run to produce renewable methanol (please see the MefCO2 project in the following sections).

4.1 H2020 projects

This section collects information on relevant EU H2020 funded projects supporting advanced alternative fuels technologies. They do not represent the full range of H_2-linked H2020 projects; this is more fully described in the LCEO TDR D2.1.13. Information was collected from CORDIS, with some review taking place of information provided on the relevant project website where appropriate.

4.1.1 Water splitting, H_2 generation and electrofuel related projects

BioAqua (Project ID: 648026) aims to use water as an electron donor for oxidoreductases, a class of enzymes used in organic synthesis to lead toward fuel production. So far, high-energy co-substrates such as glucose are used to promote oxidoreductases which sometimes have negative ethical, economic and environmental consequences. The project aims to activate water using visible light as an external energy source and chemical catalysts, linking in this way photocatalysis and biocatalysis. It aims to bridge the gap between photocatalysis and biocatalysis enabling cleaner and more efficient reaction schemes.

Photofuel (Project ID: 640720) aims at the advancement of the biocatalysts, for the production of solar-fuels. This technology start from TRL 3 and the project aims to increase it. In the frame of the Photofuel, biocatalysts are defined as microbial cells that directly excrete hydrocarbon and long chain alcohol fuel compounds to the medium from which they are separated. The best biocatalytic system(s) will be upscaled and operated outdoors in photobioreactors modified for direct fuel separation at a scale of several cubic meters (TRL 4-5). The identification of optimal future fuel blends with a fossil fuel base and Photofuel biofuels as additives, as well as the analysis of performance and emissions in car or truck engines, will be evaluated by the oil and automotive industry partners (note: does include work on algae).

SUN-to-LIQUID (Project ID: 654408) intends to establish a non-biomass non-fossil path to synthesize renewable liquid hydrocarbon fuels from H_2O, CO_2 and solar energy. It aims to advance solar fuel technology from the laboratory (TRL 3 or 4, to TRL 5) since the first production of solar jet fuel has been recently demonstrated at laboratory scale. Expected key innovations include an advanced high-flux ultra-modular solar heliostat field, a 50 kW solar reactor, and optimized redox materials to produce synthesis gas that is subsequently processed to liquid hydrocarbon fuels. Appears to improve TRL; a research/fuel production facility has been built in Spain, the project is providing a series of recommendations which the proponents believe will improve commercial exploitation.

STORE&GO (Project ID: 691797) this project is working to bring PtG technology, namely Power-to-Methane together with various innovative methanation processes, currently at a TRL 5, close to maturity (namely TRL 6-7). The project hopes to demonstrate this technology at a considerable scale between 300 kW and 1 MW in three different demonstration environments (in Italy, German and Switzerland). It also intends to add to the demonstration by also having considerable economic and logistics and placement analyses. Appears to be improving TRL, a demo plant is now in operation.

4.1.2 Projects using CO_2 & carbon gases linked to further fuel production

ACETOGENS (Project ID: 741791) Acetate-forming bacteria (acetogens) can be used in bioreactors to reduce CO_2 with hydrogen gas, carbon monoxide or an organic substrate producing biofuels or platform chemicals. This project aims at providing basic knowledge about metabolic routes and their regulation in the acetogenic model strain *Acetobacterium woodii* - which has the ability to fix CO_2. Unravelling the function of "organelles" (a subunit within a cell which has a specific function) found in this bacterium and exploring their potential as bio-nanoreactors for the production of biocommodities is intended to pave the road for the industrial use of *A. woodii* in energy (hydrogen) storage. This project is of interest principally as it could develop pathways for using CO_2 as a feedstock to make fuel, as opposed to (for example during fermentation), producing CO_2 while making a biofuel.

C2B (Project ID: 744548) aims to use flue gases from factories (cement plants, power plants and refineries) as a feedstock to produce n-butanol (a possible drop-in fuel to replace gasoline), using a proprietary microbial strain owned by a company called Oakbio. This strain utilizes CO_2 from any flue gas and H_2 as a feedstock to produce n-butanol. N-butanol can be used to make durable acrylic plastics or a biofuel. The process proposed will allow factories to cut 70% of their direct GHG emissions and aims to generate an (estimated) return of EUR 25 per t CO_2 captured. The project successfully made investigations which would likely improve operation of a pilot plant.

EMES (Project ID: 744317) microbial electrosynthesis (MES) provides a synthetic route for the production of valuable products through the reduction of CO_2. In MES, certain microbes capture electrons from a negatively poised electrode and thus convert CO_2 to fuels (and high-value chemicals). The project intended to develop highly efficient cathode materials using hollow nanostructures and three dimensional graphene scaffolds to maximize biofuel production through MES. Also, the project aimed to design a p-type CaFe2O4 semiconductor/Shewanella biofilm hybrid system as a photobiocathode to power MES with solar light through photo-generated electrons. Finally, it was intended that a novel analytical technique would be developed to visualize the metabolic activity of the cathode-attached microbes using a fluorescent dye. While the project has been completed, updates on deliverables were not yet available for review at time of writing.

ENGICOIN (Project ID: 760994) aims to develop, from TRL3 to TRL5, three new microbial factories (MFs) integrated in an organic waste anaerobic digestion (AD) platform, based on engineered strains exploiting CO_2 sources and renewable solar radiation or H_2 for the production of value-added chemicals, namely:

MF.1) the cyanobacteria *Synechocystis* to produce lactic acid from either biogas combustion flue gases (CO_2 concentration ~15%) or pure and costless CO_2 streams from biogas-to-biomethane purification.

MF.2) the aerobic and toxic metal tolerant *Ralstonia eutropha* to produce PHA bioplastics from biogas combustion flue gases and complementary carbon sources derived from the AD digestate.

MF.3) the anaerobic *Acetobacterium woodii* to produce acetone from the CO_2 stream from biogas-to-biomethane purification (TRL3 to TRL5).

Phase 3 of the project – the final phase – it is hoped will show some of the results of the work.

STEELANOL (Project ID: 656437) aims to produce bioethanol via an innovative gas fermentation process using off-gases emitted by the steel industry. The Blast Furnace/Basic Oxygen Furnace (BF/BOF) gaseous emissions are an unavoidable by-product from the steelmaking process and are currently used for electricity production (or possibly being flared). Nevertheless, they can be used to produce bioethanol, thereby reducing the usage of fossil fuel molecules in transport applications, and thus reducing GHG emissions (although displacement effects would need to be accounted for in the event the energy containing off-gases are used to generate useful heat and power for the factory). The project aims to bring the technology all the way to TRL 8 or 9, by building and operating a 25 000 tonne/year demonstration plant, construction of which is now said to be underway.

SUNRISE (Project ID: 816336) aims at promoting a large-scale research initiative to provide solutions enabling the transition to a circular economy powered by sunlight through the sustainable production of fuels (and chemicals). In November 2019 the project released an extensive technological roadmap built on knowledge from a broad group of European scientists. It hopes to capitalise on the current efforts in the areas of solar electricity and electrochemical processes, and one of its focus points is on the capture of CO_2.

SYBORG (Project ID: 637675) this project is focussed on exploiting the principle of reductive carboxylation, as a method to fix CO_2, with applications in the fuel production area. Basic research will enable the engineering of novel carboxylation reactions and products. Moreover, optimal artificial ("synthetic") CO_2-fixation pathways that are based on reductive carboxylation and that have been calculated to be kinetically and bio-energetically favoured compared with naturally existing CO_2-fixation pathways will be selected, in the hope of developing the first functional in vitro module for CO_2-fixation, a "synthetic organelle". The optimised in vitro pathways will be implemented in isolated chloroplasts, as well as alpha-proteo-bacterial hosts to create novel CO_2-fixing organelles and organisms, the scale of the work will be at laboratory. The project appears to have produced a large amount of scientific publications.

4.1.3 Other projects

ELECTHANE (Project ID: 673824) aimed to commercialise a biological process to convert CO_2 and H_2 (after electrolysis of renewable electricity) to CH_4. Project concept intends to help offer a solution to inherent imbalances in the energy grid, by converting excess electricity to H_2 and using (waste) CO_2 to produce CH_4 that can be injected into the gas grid (they planned to build a demonstration plant in phase 2 of the project). The final report appears still not obtainable, but the interim report noted positive progress towards achieving its aims was being made by the project.

MefCO2 (Project ID: 637016) aimed at encompassing flexible (with regards operation and feed) methanol synthesis with high CO_2 concentration input streams, originating from thermal power stations. The project did successfully build and operate a pilot plant which was installed at a coal plant. The other synthesis reactant, hydrogen, is obtained from water hydrolysis using surplus renewable energy - which could be difficult to return to the grid. The project appears to have been successful, with the pilot methanol plant operating at a production rate of 1 tonne/day.

MetEmbed (Project ID: 745967) applicable to enhancing energy storage, through the production of H_2. It aims at developing and applying quantum mechanical (QM) methods targeted at metalloenzymes, for which the methods in use today often fail. The target enzymes of the project are hydrogenases and polysaccharide monooxygenases (PMOs). Hydrogenases mediate the reversible conversion of dihydrogen into hydride ions and protons, while PMOs have shown great potential for biofuel production. The MetEmbed project aims to predict energetics with a new level of confidence for two systems with high potential in the areas of energy efficiency and low-carbon energy production. Low TRL but any advances made would have possible applications to larger scale projects, using such enzymes.

Plasmapower (Project ID: 735818) aimed at using the PlasmaPower technology to transform products including waste or low-value streams (e.g. woodchips, nut shells, crop & farm wastes, paper, plastic and MSW) into high energy. The project used a plasma cracking system to produce a syngas (H_2 enriched and tar-free). The project claimed that when compressed into an engine to generate electricity, it resulted in a greater than 40% electrical efficiency (vs. 25-30%; which is what the project considered typical performance by other solutions available at that time).

5 Technology development outlook

Bringing most of the advanced alternative fuels considered in this report to the point of production, at any significant scale, requires processes that are generally currently still being developed at lab-scale, although they may be starting to have applications at larger (pre-commercial or demonstration stage), as discussed in the technology state of the art section. Commercial production of such fuels is not yet the case anywhere in the world, principally due to production costs being too high and/or technical barriers that still need to be overcome. An exception to the above is power-to-gas, which is beginning to become more popular - although the majority of these projects are for hydrogen production, as opposed to the synthesis and production of other fuel molecules using hydrogen as a feedstock. Thema et al (2019) clarify that many of the power-to-gas projects they encountered are smaller scale pilot plants with 1-3 year lifespans.

A number of technological trends are observed in each sector, and the needs to address key constraints are summarized. Given the dominance of high costs as a limiting factor to the proliferation of certain fuel technologies (as opposed to only technical difficulties), there is a consideration of economics, e.g. projections of CAPEX and OPEX, where most appropriate. However most of the technological pathways analysed are at very low TRL, therefore consequent economic analysis may lack elements. It is proposed therefore to focus on an evaluation of the main barriers to large scale deployment, and to try to identify possible solutions.

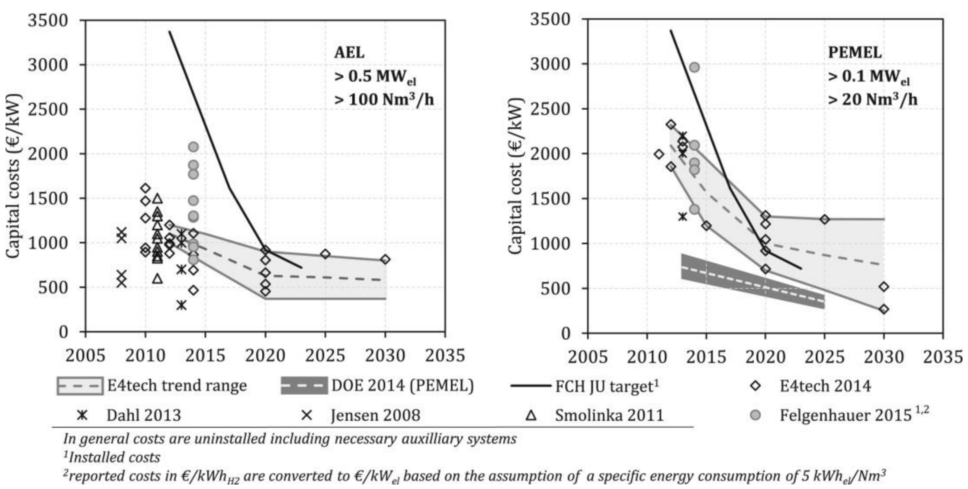
5.1 Technology trends and needs

5.1.1 H_2 production and Electrofuels

For this section, the main technology need identified is really to try and lower costs which can considerable. While such issues for H_2 production have been addressed in LCEO TDR (Deliverable D 2.1.13 *Fuel Cells and Hydrogen*), here they have been summarised and complemented with other researches based on literature review.

The review indeed reveals significant differences among the studies, resulting in a broad range of electrofuels production costs. A recent review study carried out by Brynolf (Brynolf et al., 2018) proposes a range of EUR 10–3 500/MWh; considering an average LHV of 44 MJ/kg, the range per ton of fuel is EUR 120–42 000/ton. According to Cerulogy (2017), production costs in the near term are likely to be EUR 3 000/ton of electrodiesel (or electrojet or electropetrol), a possible reduction is a scenario with a low electricity cost of 5 cEUR/kWh and a facility with 50% conversion efficiency.

Figure 11. AEL and PEMEL capital costs, source Buttler and Spliethoff (2018).



Hydrogen production via electrolysis represents today the major proportion of the investment costs (CAPEX) for PtG and PtL plants. A review carried out by Buttler and Spliethoff (2018) allows defining CAPEX in the range of EUR 800–1500/kW_{el} for Alkaline Electrolysis (AEL); for installations above 500 kW. Polymer Electrolyte Membrane Electrolysis (PEMEL) system costs are almost twice as high with given uninstalled costs ranging from EUR 1300-2200/kW_{el}. Due to the pre-commercial status of Solid Oxide Electrolyser Technology (SOEL), there is a high level of uncertainty about investment costs.

In a recent E4tech study (E4tech, 2018), cost reduction trend lines are derived based on stakeholder consultations; in a central scenario the mid-term cost reduction in AEL was set at about EUR 630/kW_{el} by 2020 and EUR 580/kWel by 2030 (central scenario). For the innovative SOEL, E4Tech sets expected commercial costs in EUR 2000/kW_{el} between 2012 and 2020, EUR 1000/kW_{el} between 2020 and 2030, with a long term target of EUR 300/kW. The operational costs per year (excluding electricity) are often provided, based on a percentage of the CAPEX. The E4tech study reports OPEX in the range of 2–5% of the CAPEX.

Production of electro fuels from renewable Hydrogen and CO_2 is recognised as of great interest for the medium term. The potential of using renewable electrical energy peaks which may be otherwise wasted, is a strong strategic advantage, by being able to increase the RES plant availability and average productivity. In addition, the possibility to temporarily fix CO_2 streams, ether from biological sources or not, makes the technologies attractive for a wide range of stakeholders. Finally, conversely to H_2 as a fuel option, eFuels production technologies potentially produce a drop-in fuel, ready to be blended without the need to develop specific infrastructures. All these points considered, it is possibly better to discuss the current challenges as a need to reduce costs, rather than technological barriers potentially limiting further development. Cerulogy (2017) state that while many of the technological steps required for liquid electrofuel production are now widely used in other industries, some parts of the chain have lower TRLs. The full process from electricity to synthetic fuel has not yet been demonstrated at commercial scale (although pilot scale facilities exist). There appears to be a trend at least in Germany towards PEM-type electrolysers instead of AEL-type (TÜV SÜD, 2020), although Thema et al (2019) note in terms of electrolyser technology, from an overall point of view, half the projects they investigated use PEM, the other half AEL.

5.1.2 CO_2 capture and utilization

The topic of carbon capture has been addressed in a recent report for LCEO: TDR Carbon Capture, Utilisation and Storage (CCUS), 2018. Moreover technologies for capturing CO_2 from biogas streams have been comprehensively presented in the Deliverable D2.2.12 for the LCEO; Technology Development Report Sustainable Advanced Biofuels (2018). Of more interest for this report, is to comment on current barriers to the further development technologies for CO_2 utilization, in particular for fuel production purposes. It is worth remarking that, apart from a specific case, the technologies presented are all at low TRL, hindering to a large extent an accurate consideration of their expected CAPEX and OPEX, as well as enabling useful detail on likely final fuel production costs. In the specific case of gas fermentation, this information is scarcely available, as it is a propriety technology, developed mainly by a single operator. The company itself reports their success in overcoming the main barriers for commercialization and in a recent press release (Lanzatech, 2018a) announced the start-up of their first commercial plant.

5.2 Patents

Despite the relatively recent nature and general trend of low TRL in the technologies studied, a consideration of patents was carried out, using targeted searches of the European Patents Office tool, and a relatively small number of patents were uncovered. The searches have been aided somewhat, given the fact there is a dominant or sole-technology provider in certain cases. For microbial fermentation, a search was carried out, and specifically targeting the key company Lanzatech who are certainly the main company behind this technology. The search yielded 678 patents linked to this company, but considering that they are not only focussing on the production of fuel, the search was refined further to mirror their main fuel molecule, ethanol, resulting in 53 patents worldwide.

Using the EPO tool with "CO_2" + "fuel" + "synthesis" as query yielded 628 results. Afterwards, the results were refined using PTG as the query, and this resulted in 88 results. Respectively, the result for "power-to-gas" was 7 results. When "ptl" + "fuel" were used as keywords the result was 5 patents and when "power-to-liquid" itself was used, the result was 1 patent.

A similar situation was seen in the area of fuel from waste, which is dominated by a small number of companies; Canada's Enerkem have filed 53 relevant patents, while the European (UK based) company Velocys, have 11 patents - but again refining the queries to the fuel sector and/or FT, the number of found patents reduces to 5.

5.3 Main barriers to deployment

The main barriers hindering the deployment of the technologies analysed in this report can be broadly categorised as follows. Costs remain the significant barrier for electrofuels, as the individual steps for their production are in existence, but the linkage to make the fuel production pathway complete is still lacking, certainly at large scale (excluding power to gas). A secondary barrier would be the likely large extra loading on electricity grids, and possibly – if electrofuels production was to take place in large volumes – the associated extra need for new renewable electricity could be highly significant, and would have to be taken into account. Improved electrolysis systems, which maximise H_2 production, while proving robust in operation and at pressure, would be an improvement.

Within the area of water splitting, the energy inputs remain significant, and the question of how to handle the resulting H_2 remains. The direct use of H_2 as a fuel is restricted somewhat by infrastructure to provide the fuel, plus the appropriate vehicles would need to be in circulation in order to be able to use the fuel.

Regarding fuel synthesis, and how to combine the H_2 (and carbon gases), PtG while improving overall chain efficiencies remains hampered by costs. PtL (using Fischer-Tropsch) has been shown to work at large scale, but the challenge is to show the technology can work well at a lower scale - and thus match this technology to the likely available CO_2 sources. For PTL involving methanol synthesis, it also works, but the high process pressures are seen as an issue to be improved.

Regarding CO_2 capture, general improvements in this system continue, with a view in particular, to try and reduce the energy inputs required for operation. For a more in-depth consideration, it is suggested to review the aforementioned LCEO report on CCUS. Gas fermentation is a pathway somewhat dominated by one player, and while it does appear to be progressing, this remains difficult to independently verify. Most recently there have been reports that their pilot/test plant in China is operating successfully, and produced in the region of 27 000 tonnes of ethanol in its first 12 months of operation. It will be useful to continue to monitor how this pathway progresses.

6 Conclusions & Recommendations

The term advanced alternative fuels covers a broad range of fuel production pathways, and they appear to hold a considerable degree of promise, in particular as possible options to aid the decarbonisation of the transport system. These fuels are taking new approaches to fuel production, such as by trying to make use of excess renewable electricity, or by recycling CO_2 and using it as a feedstock, thus aiming to avoid some of the pitfalls of other more traditional fuel production pathways which dominate the landscape today. There are nonetheless some drawbacks to these technologies, not least linked to their relatively new nature and low TRL. It is suggested that R&D efforts are aimed in certain areas to help overcome these difficulties and give the technologies a better chance to move toward production.

This report is somewhat unique, as certain fuel pathways are largely based on technologies that are of interest to other energy sectors. For electrofuels, this is particularly apparent, as they use both H_2 (renewable) and carbon (CO_2), which can be from both biomass and fossil based sources.

For **electrofuels**, individual steps of the production chain are available at high TRL, but a complete and large-scale production chain for liquid fuels appears not yet to be in existence (although progress is being made in power to hydrogen and in power to methane most notably in Germany). The advantage of electrofuels is that they can be a method for converting excess renewable electricity into liquid fuels, and thus become an energy storage medium. For this pathway, production costs appear to be a considerable drawback, and thus work to alleviate this could prove useful in increasing the TRL of entire production chains. Indeed Schmidt et al (2018) note the main requirement towards their large-scale implementation is a continued cost reduction in particular of renewable hydrogen production from water electrolysis powered by solar and wind energy. The critical importance of electricity price is also noted by Cerulogy (2017). Important secondary considerations would be the large effect on the electrical grid in order to supply enough power to production units. In the medium-term, there is a strong need for alternative fuels, in particular in aviation, while for the other transport modes, an important further aspect would be to look at the direct use of the renewable electricity in transport, which appears currently to be more energy efficient.

With regard to renewable hydrogen supply for electrofuels, alkaline **electrolysis** (AEL) is said to be the most mature technology, with the lowest specific investment and maintenance costs. Other electrolysis systems; PEMEL and AEL, offer fast load dynamics, while SOEL can potentially increase the efficiency of hydrogen production but need to be made more robust for industrial operations. Using the growth in Germany as a guide, it appears that PEM type electrolysers are gaining popularity relative to AEL-type. Research focussing on part-load electrolyser operation is seen as being a particular area of interest, as it will help enable the use of power from variable renewable sources, possibly curtailed power which is otherwise not being used. For photo-electrochemical **water splitting** (PEC), while efficiencies of the process are improving, work continues to make the process scalable and affordable. Hydrogen certainly can be used directly as a fuel, but direct use in electrofuels negates the need to change engines for fuel combustion or develop refuelling infrastructure, which is particularly interesting for the aviation sector.

Fuels using carbon in the form of CO_2 or CO are also the subject of growing interest. For technologies looking at **CO_2 capture** it is advised to see the other LCEO report focussed on this area. Nonetheless, it is noted that amine based PCC is favoured, linked to single-stream emission sources (such as the cement industry or power plants).

Regarding the **fuel synthesis part** of electrofuels, it has been seen that a number of options are available, which utilise Fischer-Tropsch technology, or methanolysis (to produce hydrocarbon fuels or alcohol fuel respectively). Power-to-Gas (PtG) has overall chain efficiencies approaching that of large thermal power plants, but costs remain a large inhibiting factor, while Power-to-Liquid (PtL) - employing FT which itself has worked at large scale - but now attempts are being made to ensure it succeeds at a lower scale more suitable to match the likely available volumes of the most favourable CO_2 sources. Whereas for PtL, methanol synthesis is also largely functional, but work is on-going to try and reduce the operating pressures of such systems.

Alternatively to thermo-chemical processes, **microbial fermentation**, in which microorganisms are fed by carbon containing gases, have gained a lot of attention and coverage. One company are the dominant party in this area, and it is of interest to note they announced during the middle of 2019 their production chain was going into industrial scale production (with a c.45 000 ton/annum facility) in China. The large H2020 project in which the company are involved in appears (at time of writing) to be behind their original schedule but is progressing. The carbon gas sources may be fossil based, but the technology is likely to be transferrable to bio-carbon sources also. However if the feedstock gases used as a feedstock for this process were already being used as a fuel (to provide process heat or power), this would need to be taken into account.

Internationally, it would be advisable to note progress from other principle regions in this area, along with significant multi-national or global information sources such as the IEA, and to see how new initiatives and work plans on these relatively new technologies develop. It is encouraging that Thema et al (2019) found that certainly for PtG the global focus of research and application of this technology is in Europe, but progress in the US is also increasing. Finally, if a fuel can save GHG emissions compared to the regular predominant fuels (and in a verifiable manner such as via a robust life cycle analysis which takes into account the existing uses of feedstock materials[5]), it would seem a rational approach to include such fuels in future analyses of advanced alternative fuels, even if the pathway is not entirely renewable.

[5] The existing use of a feedstock is also relevant for electrofuels. On this point, Searle (2018) suggests MS require electrofuel producers submit “GOplus” certificates that would show the renewable electricity used has not already been directly counted toward the RED II renewable energy target

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List of abbreviations and definitions

AAF Advanced Alternative Fuels

AEM Anion Exchange Membrane

AEL Alkaline Electrolysis

ATO Antimony doped tin oxide

ATR Auto-thermal Reforming

AWP Annual Work Plans of the FCH JU

CAPEX Capital Expenditures

CCS Carbon Capture and Storage

CCUS Carbon Capture Utilisation and Storage

CHP Cogeneration of Heat and Power

CNG Compressed Natural Gas

CORDIS Community Research and Development Information Service

DME Dimethyl Ether

DOE Department of Energy

EC European Commission

EPO European Patent Office

EU European Union

FC Fuel Cell

FC&H Fuel Cells and Hydrogen

FET Future Emerging Technology

FP6 6th Framework Program

FP7 7th Framework Program

FT Fischer Tropsch

GHG Green House Gas

H2020 Horizon 2020 Program

HHV Higher Heating Value

IEA International Energy Agency

IEE Intelligent Energy Europe

IPC International Patent Classification

JCAP Joint Centre for Artificial Photosynthesis

JRC Joint Research Centre

KPI Key Performance Indicators

LCEO Low Carbon Energy Observatory

LCFF Low Carbon Fossil Fuels

LHV Lower Heating Value

LNG Liquefied Natural Gas

LPG Liquefied Petroleum Gas

MAWP Multi-Annual Work Program

MEA Membrane Electrode Assembly

MS Member State

MW Mega Watt

Nm3 Normal cubic meter

O&M Operative and maintenance (costs)

OPEX Operational Expenditures

PEC Photo-Electrochemical Water Splitting

PEM Proton-Exchange Membrane

PEMEL Polymer Electrolyte Membrane Electrolysis

PMO Polysaccharide monooxygenases

PtG Power-to-Gas

PtH Power-to-Hydrogen

PtL Power-to-Liquid

PtX Power-to-X

RDI Research Development and Innovation

R&D(D) Research and Development (and Demonstration)

RED Renewable Energy Directive

RES Renewable Energy Sources

SET Strategic Energy Technology

SotA State-of-the-art

SOEL Solid Oxide Electrolysers

SOFC Solid Oxide Fuel Cell

SMR Steam Methane Reforming

TDR Technology Development Report

TCR Thermo-Catalytic Reforming

TRL Technology Readiness Level

TWG Technical Working Group

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Annexes

Annex 1. State of the Art of PCC technologies

Table 6. State of the art of PCC technologies (Yu, 2018)

Technology provider	Solvent	Comments
Shell Cansolv	Cansolv chemical solvents	The first commercial PCC plant in a coal-fired power station came into operation at the SaskPower Boundary Dam Power Station in October 2014. The project uses Cansolv's amine-based SO2 and CO2 capture technology with a capture capacity of ~ 1 million tonnes/yr.
		The total capital investment for the project was more than CAD$1.4 billion. The CO2 capture plant cost more than CAD 800 USD million. The project was the first of its kind. SaskPower claimed that the total capital cost of future plants could be reduced by 20%–30%.
MHI	KS-1 sterically hindered amine solvent	NRG Energy and JX Nippon Oil & Gas Exploration are jointly carrying out the Petra Nova Carbon Capture Project at WA Parish Power Plant at Thompsons, near Houston, Texas. The WA Parish project will use the KM-CDR process, with a proprietary KS-1 high-performance solvent used for CO2 absorption and desorption. The CO2 capture capacity is 1.4 million tonnes per annum. The plant is the world's largest CCS project from a coal-fired power station and has been operational since 2017.
		MHI claims that the KM-CDR circulation rate is 60% of that for (unspecified) monoethanolamine (MEA), the regeneration energy is 68% of MEA, and the solvent loss and degradation are 10% of MEA. MHI is working on process improvements said to have the potential to reduce the regeneration heat requirement from 2790 to 1860 kJ per kg of CO2.
Fluor	Econamine FG Plus	Fluor's Econamine FG Plus technology is claimed to reduce steam consumption by more than 30% compared with 'generic' MEA technology and has been used in more than 25 commercial plants for the recovery of CO_2 from flue gas at rates from 6 to 1000 metric tonnes per day.
		The technology has been applied to demonstrate removal of CO2 from flue gas at E.ON's Wilhelmshaven coal-fired power plant. The Wilhelmshaven pilot plant can capture 70 t per day when operating at full capacity.

GE	Advanced amine solvent	Dow Oil & Gas and GE are jointly developing an advanced amine process technology that uses UCARSOL™ FGC 3000, an advanced amine solvent from Dow, in combination with advanced flow schemes. The demonstration plant was located at the EDF thermal power plant in Le Havre, France, and captured its first tonne of CO2 in July 2013. The test program was completed in March 2014.
		The technology has successfully been demonstrated in the field at > 99.9% pure CO2 product quality at 90% capture rates. The process design has been optimised for emissions mitigation and control and has less solvent degradation than MEA.
Babcock & Wilcox Power Generation Group, Inc.	OptiCap	Babcock & Wilcox completed a three-month test campaign in 2011 using OptiCap solvent. The test run spanned approximately 2000 h.
		The solvent has low corrosivity and regeneration energy, and an expected high resistance to solvent degradation. The lowest regeneration energy measured was 2.55 MJ per kg of CO2. In addition, the capture process can be operated at elevated pressures due to the solvent's thermal stability, which will significantly reduce the mechanical compression energy requirement.
Aker Clean carbon (ACC)	ACC proprietary solvents	ACC tested its solvent at the CO_2 technology Centre Mongstad in 2012. ACC advanced solvents S21 and S26 had good energy performance and were superior to 30 wt% MEA with respect to solvent degradation, ammonia emission and nitrosamine formation. For example, the reboiler duty for S21 and S26 was approximately 10% lower than that for MEA. Solvent amine losses were approximately 2.6 kg amine per tonne CO_2 captured for MEA, 0.5–0.6 kg amine per tonne CO_2 captured for S21, and 0.2–0.3 kg amine per tonne CO_2 captured for S26.
Siemens	Postcap	The Postcap technology is based on a biodegradable amino-acid salt that has a very low vapour pressure, with practically no solvent vapour emitted to the environment. The solvent has a high selectivity to CO2 and a good absorption property, which leads to high purity of CO2 product and use of less solvent. The specific heat required in the process amounts to around 2.7 GJ per tonne of CO2 separated. The technology was verified in a pilot plant at the E.ON coal-fired power plant Staudinger near Frankfurt, Germany.
BASF	OASE blue	The OASE blue amine-based technology was developed as an optimised large-scale PCC technology. It has low energy consumption, low solvent losses and an exceptionally flexible operating range. Testing using a 0.45-MWe pilot plant using lignite-fired power plant flue

		gas showed that the solvent was stable; little degradation was observed over 5000 h, whereas the reference MEA solvent started to degrade appreciably under the same conditions.
		Linde is refining a PCC technology incorporating BASF's OASE® blue-based process to reduce regeneration energy requirements by designing, building, and operating a 1-MWe equivalent slipstream pilot plant at the National Carbon Capture Center.
University of Texas at Austin	Piperazine-based solvent	Compared with MEA-based solvents, piperazine-based solvents are more stable, have a faster CO2 absorption rate and higher capture capacities and allow high-pressure generation. Pilot-plant trials at the university have shown that with an advanced flash stripper, the capture process based on 5 M piperazine (mole·kg− 1 water) can achieve regeneration energies of 2.1–2.5 GJ per tonne CO2.
China Huaneng Group	Amine-based solvents	The China Huaneng Group has been operating an amine-based PCC demonstration plant at Shanghai Shidongkou No. 2 Power Plant since 2009. The CO2 capture capacity is 100000–120000 t per annum. The chemical composition of the solvent is not reported in the open literature.
CO_2CRC (Australia)	Precipitating potassium carbonate	CO2CRC's UNO MK 3 technology uses a precipitating potassium carbonate (K2CO3) process. It has many advantages over conventional amine processes, including low energy usage for regeneration, low overall cost, low volatility and environmental impact, multi-impurity capture and production of valuable by-products. The technology was demonstrated in an Australian power station capturing one tonne of CO2 per day from power plant flue gas.

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