European Commission

METIS Studies

Study S8

The role and potential of Power-to-X in 2050

METIS Studies
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1. ABBREVIATIONS AND DEFINITIONS

1.1. ABBREVIATIONS

Abbreviation	Definition
CAPEX	Capital expenditures
CCS	Carbone Capture and Storage
CH_4	Methane
CO_2	Carbon dioxyde
CO	Carbon monoxyde
EU ETS	European Union Emissions Trading Scheme
FCV	Fuel Cell Vehicle
FLH	Full-Load Hours
FQD	Fuel Quality Directive
H_2	Hydrogen
HHV	High Heat Value
HRS	Hydrogen Refuelling Station
ICE	Internal Combustion Engine
Mt	Millions of tons
kW_{el}, kW_{H2}, kW_{CH4}, kW_{PtL}	Kilo-watt (specifying the physical quantity: electric power, hydrogen, methane or liquid hydrocarbons)
MWh_{el}, MWh_{H2}, MWh_{CH4}, MWh_{PtL}	Mega watt-hour (specifying the physical quantity: electric power, hydrogen, methane or liquid hydrocarbons)
OPEX	Operating expenses
PEM	Proton Exchange Membrane
RES	Renewable Energy Sources (solar PV, wind onshore and offshore)
SMR	Steam Methane Reforming
SOEC	Solid oxide electrolyser cell
t_{CO2}	Tons of CO_2
TWh	Tera watt-hour

1.2. DEFINITIONS

Concept	Definition
Power-to-X	Conversion of power from the electricity sector into another energy carrier
Power-to-H_2	Conversion of power into hydrogen
Power-to-CH_4	Conversion of power into methane, as substitute for natural gas
Power-to-Liquids	Conversion of power into liquid hydrocarbons
Biomass-to-CH_4	Conversion of biomass into methane (biomethane)

Biomass-to-Liquids	Conversion of biomass into liquid hydrocarbons (biofuels)
Threshold electricity price	Electricity price below which a given power-to-X technology can be competitive

1.3. METIS CONFIGURATION

The configuration of the METIS model used to evaluate the different power-to-X technologies is summarised in Table 1.

Table 1: METIS Configuration

METIS Configuration	
Version	METIS v1.4
Modules	Power system module, Capacity expansion module, Demand module
Scenario	METIS EUCO30 2050 scenario
Time resolution	Hourly (8760 consecutive time-steps per year)
Spatial granularity	Member State

2. EXECUTIVE SUMMARY

Within the 2015 Paris Agreement, the European Union has committed to climate action to keep warming well below 2°C above pre-industrial levels. According to the scientific community of the Intergovernmental Panel on Climate Change (IPCC), this implies that GHG net emissions fall to a level close to zero shortly after 2050 and that all energy sectors reduce drastically their emissions.

The emissions from the power sector are successfully reduced and a full decarbonisation by the year 2050 appears manageable. Instead, the transport, buildings and industry sector, which still rely primarily on gas and liquid fossil fuels, are the sectors with the highest carbon abatement costs. In this context, power-to-gas and power-to-liquid solutions, together with the development of low-carbon electricity generation capacities appear to be promising solutions.

The objective of this study is to evaluate under which conditions power-to-gas and power-to-liquid (referred to as power-to-X technologies in this document) can compete with alternative low-carbon production processes by the year 2050. A literature review is realised in order to gather technical and economic information about various power-to-gas and power-to-liquid technologies, along with competing solutions. For three different use cases (plus two sensitivities), the study estimates the costs related to generating synthetic gas or liquid, considering different technologies and CAPEX evolution. It determines the profitability of each power-to-X solution across all EU Member States, taking into account their peculiarities in terms of power generation mix and hourly electricity prices.

The prices are determined with the EU power system model METIS, which simulates the hourly dispatch of all generation, storage and interconnection capacities, considering demand-side flexibility and in particular power-to-X technologies. The capacity mix and annual electricity demand of individual EU Members States are based on the EUCO30 2050 scenario, with 65% of the EU's net electricity generation provided by renewable energies. Besides, the economic analysis focuses on the competitiveness of the first power-to-X projects compared to alternative benchmark solutions.

The analysis underlines that the profitability of power-to-X is primarily subject to the availability of low electricity prices. In the studied scenario, countries like Spain, Ireland or Greece exhibit more than 2 000 hours of near zero electricity prices due to their high shares of variable renewable energy (solar and wind energy accounts between 53% and 75% of the national electricity demand for these countries). In France, the high nuclear capacity, coupled with an increasing share of solar and wind energy, implies electricity prices below 10 €/MWh during more than 2 000 hours per year.

For these countries, water electrolysis (i.e. power-to-hydrogen) appears to be a competitive solution compared to hydrogen production by Steam Methane Reforming with Carbon Capture and Storage, in particular if the electrolysers are associated with large-scale hydrogen storage: storing synthetic hydrogen (generated during periods of low electricity prices) avoids to invest in expensive back-up solutions to respond to the demand during the rest of the year.

In contrast to power-to-hydrogen, power-to-methane and power-to-liquid technologies are more capital intensive. At the same time, the generated final energy carriers are also more difficult to decarbonise as alternative carbon-neutral process chains (biomethane and advanced biofuels are considered in this report) prove costlier than the decarbonisation of hydrogen. In comparison to these alternatives, the study reveals that power-to-X technologies are competitive only in countries with more than 3 000 hours of electricity prices below 10 €/MWh, namely Spain, Portugal and Cyprus. However, this result highly depends on the evolution of the technology CAPEX, along with the cost and availability of alternative solutions. In particular, if biomethane and advanced liquid biofuel potentials are already dedicated to other uses, or if their availability is limited (due to land use constraints, other policies objectives, etc.), the utilisation of power-to-X may become necessary and competitive.

3. Introduction

By 2050, the European Union aims to reduce greenhouse gas emissions by 80-95%, compared to 1990 levels. As the full decarbonisation of the power sector by the year 2050 appears to be manageable, part of the final energy use in other sectors could be switched to low-carbon power demand to decrease their emissions. In particular, fossil gas and liquid fuels in the transport and industry sector count among those energy carriers featuring the highest carbon content. However, for some usages, the direct shift to electricity may be very costly, if possible at all (take for instance kerosene utilisation in aviation). On the other hand, electricity may be used to generate different other energy carriers, including synthetic gas and liquid fuels. Power-to-gas and power-to-liquids solutions then appear to be promising solutions to decarbonise the energy sector, in line with the development of low-carbon electricity generation capacities.

In this study, power-to-X refers to three main categories[1], corresponding to the three main synthetic products: power-to-H_2, power-to-CH_4 and power-to-Liquids, meaning the production of hydrogen (H_2), methane (CH_4) or liquid fuels.

In all three cases, water electrolysis represents the initial process in order to produce H_2 using electric power. Subsequently, different conversion processes can follow to transform H_2 into CH_4 or liquid hydrocarbons, such as methanol (MeOH), ethanol (EtOH) or dimethyl ether (DME). Figure 1 shows a schematic representation of the different power-to-X production chains and examples for the utilisation of their final energy products, such as the use of synthetic liquids and gases in the transport and industry sectors, the injection of H_2 and CH_4 into the gas grid or the reconversion of gas into power (equivalent to a long-term power storage).

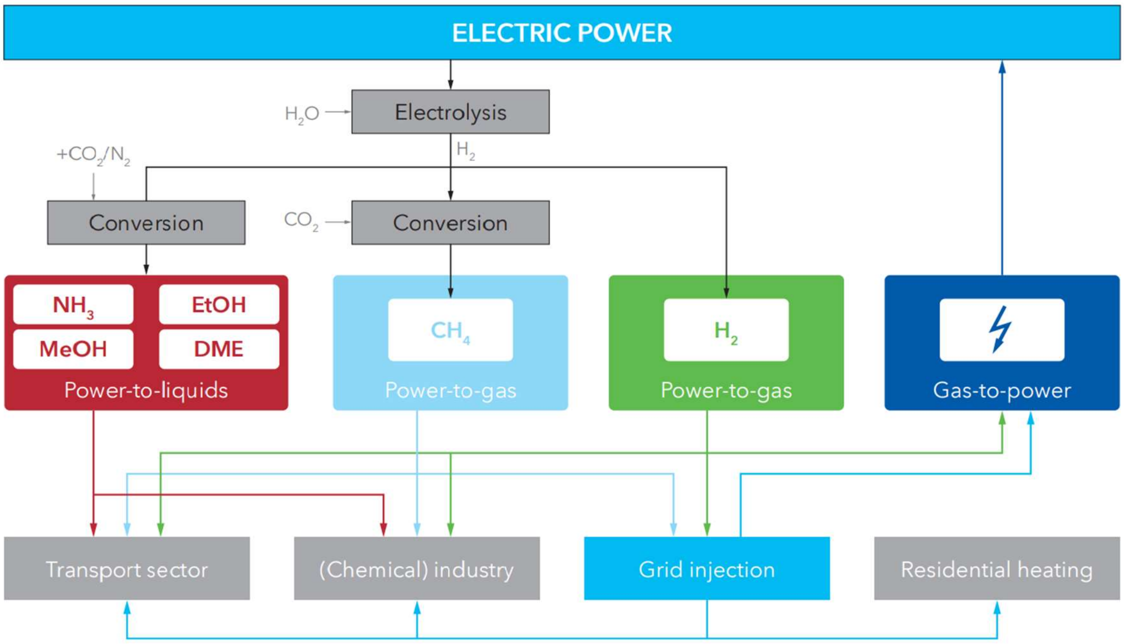


Figure 1 - Schematic representation of power-to-X [1]

This study has for objective to contribute to the current debate around the power-to-X topic by analysing the potential market uptake of power-to-X products in the EU in the year 2050 and the required conditions to ensure profitability of power-to-X technologies.

A literature survey summarises the market potentials for power-to-X products and gives an overview of the different power-to-X technologies and their technical and economic parameters (cf. Section 4).

[1] Power-to-X can also refer to power-to-Chemicals, power-to-Ammonia and power-to-Heat.

Section 5 introduces the methodology to determine under which conditions power-to-X technologies are profitable and defines a set of use cases that allow to benchmark the power-to-X technologies with competing processes. As the profitability of power-to-X technologies depends to a large extent on the electricity price, Section 6 describes market prices for the METIS EUCO30 2050 scenario and the underlying methodology. Ultimately, Section 7 sets out the results profitability of the different power-to-X technologies on a country-by-country basis.

It should be noted that the analysis presented in sections 5 to 7 were undertaken under the assumption of fixed demands for each energy vector (EUCO30 2050). For a given energy carrier X, we compare two supply sources: power-to-X and a currently mature and carbon-free source of X. Possible switches of energy carriers (e.g. direct electrification of specific usages) are not considered.

4. LITERATURE SURVEY

The power-to-X topic receives increasing attention as it is considered as particularly promising and decisive technology in the context of the EU's long-term energy system transition towards full decarbonisation. Thus, many studies have analysed the potential of power-to-X technologies, be it at a national level for single countries (for example France [2] [3], Germany [4] or United Kingdom [5]) or at the European level (cf. [6] [7] [8] [9] [10]). Several of these studies have identified the electricity price as the key factor for the future development of power-to-X (such as [2] [4] [6] [10] [9]). Other main factors for power–to-X growth are the technical and economic data of the different technologies.

This section gives an overview of the potential markets and demand for power-to-X products, followed by a detailed description of the individual power-to-X technologies and their technical and economic parameters. The latter serve as input for the model-based assessment detailed in Section 5.

The conversion processes of H_2 into CH_4 or liquids requires additional chemical educts such as CO_2 or N_2 (in ammonia production for example). As CO_2 is the most important component in the production of liquids and its accessibility might represent a serious limitation for synthetic CH_4 and liquids production by the year 2050, Sub-section 4.5 provides additional insights on the technical and economic parameters of CO_2 capture.

4.1. POTENTIAL DEMAND FOR POWER-TO-X PRODUCTS

The market analysis has for aim to estimate the potential demand for power-to-X products by the year 2050 in different end-use sectors, namely the industry sector, the transport sector and the potential injection of H_2 and CH_4 into the gas grid.

4.1.1. POTENTIAL DEMAND FOR POWER-TO-H_2

- **Industry**

Currently, almost all H_2 production is dedicated to industrial processes. In Europe, H_2 industrial consumption accounts for 8.25 Mt out of the total 8.8 Mt produced. From the industry demand, 47% is used for refineries, 39% for ammonia industry, and 14% for other chemical industries and metallurgy [11]. The *CertifHy* project forecasts for H_2 demand an annual growth of 3% [7]. Their projection matches projection from Hydrogen Council [12] with an approximatively annual demand of 470 TWh for 2030 (cf. Figure 2).

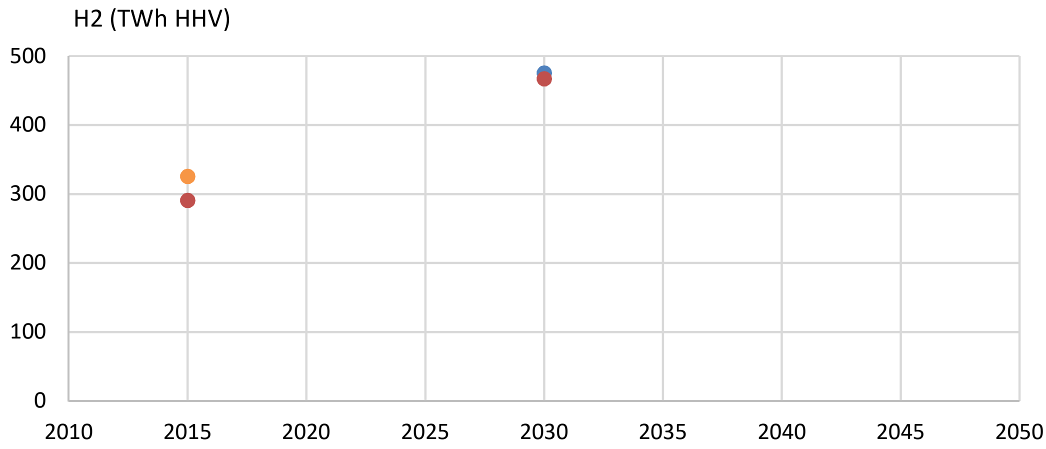


Figure 2 - Literature survey of the H_2 demand projection for industry in Europe (unspecified spatial perimeter except for CertifHy (EU28)). Orange dot is AFHYPAC [11], red is CertifHy [7] and blue is Hydrogen Council [12].

In contrast to power-to-H_2, the conventional production of hydrogen typically emits CO_2, as it relies on natural gas as major source material (for further details see Section 4.2.2). Hence, the use of synthetic hydrogen represents an opportunity to decarbonise the before-mentioned industry sectors (potentially triggered by price high CO_2 prices signals from the European Emissions Trading Scheme, EU ETS).

- **Transport**

Hydrogen demand for mobility is mainly driven by the development of fuel cell vehicles (FCVs) and by the regulatory framework for clean transport in the European Union (EU), especially the Fuel Quality Directive (FQD) [13], which requires fuels used for road transport to meet strict quality requirements.

CertifHy has assessed national roadmaps concerning development of H_2 mobility and has examined four countries (or group of countries) [8]. Quantitative roadmaps for the evolution of FCVs, Hydrogen Refuelling Stations (HRSs), and hydrogen consumption at the horizon 2030 and 2050 are provided (see Figure 3). Germany is the country foreseeing the highest penetration for FCVs (in absolute numbers), followed by the United Kingdom, France and a group of Scandinavian countries (Sweden, Norway, Finland and Denmark) [8].

COUNTRY	PROGRAM	FINDINGS	2015	2025	2030	2050
	H₂ Mobility	HRS	90	500	1,000	NA
		FCVs	200	500,000	1,87 mill	NA
		H2 (tons)	24	60,000	216,000	NA
	Mobilité Hydrogène France	HRS	NA	355	600	>1,000
		FCVs	NA	167,000	773,000	7.3 mill
		H2 (tons)	NA	22,000	89,000	880,000
	UK H₂ Mobility	HRS	65	380	1,150	NA
		FCVs	<500	255,000	1,27 mill	NA
		H2 (tons)	<100	30,600	152,000	NA
	H2moves.eu SCANDINAVIA	HRS	12	185	NA	450 - 1000
		FCVs	26	87,000	NA	3,3 mill – 7,3 mill
		H2 (tons)	3.2	10,400	NA	394,000 - 880,000

Figure 3 – Hydrogen-based mobility roadmaps. Source: CertifHy [8]

As presented in Figure 4, projections of hydrogen demand for mobility in Europe are estimated to range between 10 and 30 TWh by the year 2030 [7, 12]. The European Commission's EUCO30 scenario provides a more moderate projection for 2030, but expects a more important growth towards the year 2050, reaching 100 TWh.

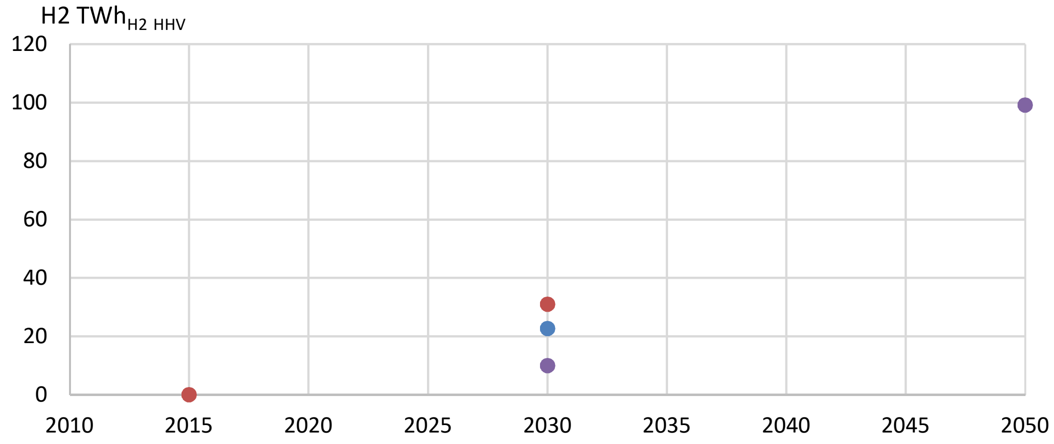


Figure 4 - Literature survey of the H_2 demand projection for mobility in Europe. Purple dots are EUCO30 scenario, red is CertifHy [7] and blue is Hydrogen council [12].

- **Gas grid injection**

Projections of hydrogen demand dedicated to the injection into the gas grid (for the purpose of decarbonising the gas sector) is directly related to the natural gas demand and the ability of the grid to blend natural gas with hydrogen. The extent to which hydrogen can be injected into the gas grid depends on each country's policies. The maximum thresholds of selected countries are given in Figure 5.

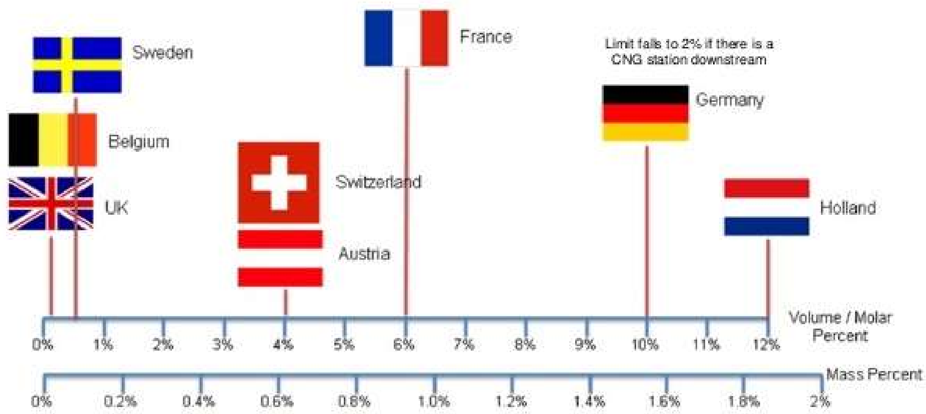


Figure 5 - H_2 blending limit into natural gas grid for selected countries [14]

CertifHy [7] assumes that a hydrogen volume ratio of 1% within the total natural gas demand could be realised in 2025 without any technical constraint. This rate is assumed to increase up to 2% in 2030. Hydrogen Council [12] estimates that even a rate of 5 to 20% could be handled by the current gas grid depending on the infrastructure quality. Both projections are included in Figure 6.

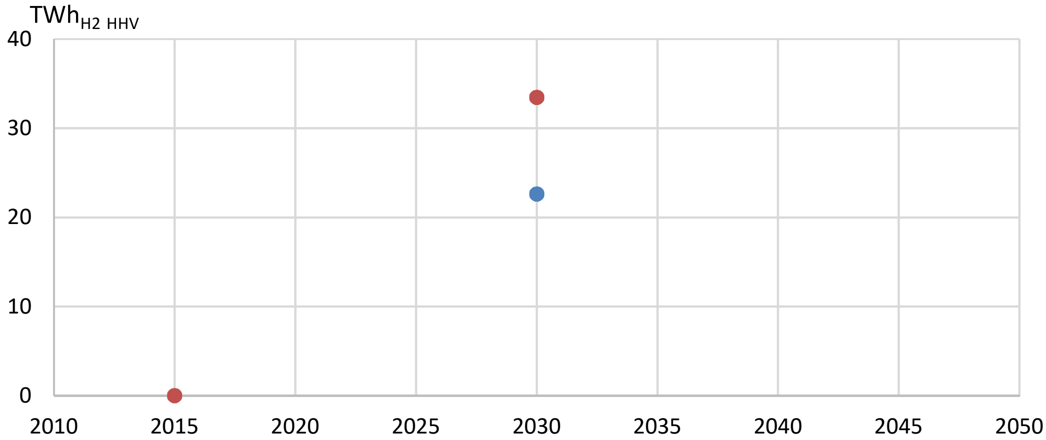


Figure 6 - Literature survey of the H_2 demand projection for gas grid injection in Europe. Blue dot is Hydrogen council [12] and red dots are CertifHy [7].

Decarbonising the energy sector could lead to replacing natural gas and fossil liquids by CO_2-free CH_4 and liquids, which can create an additional demand for H_2. Indeed, H_2 can be converted to synthetic CH_4 and synthetic liquid fuels using power-to-X technologies. The two following sections provide some elements to assess the potential demands for power-to-CH_4 and power-to-Liquids products.

4.1.2. POTENTIAL DEMAND FOR POWER-TO-CH_4

As a substitute of fossil gas, power-to-CH_4 demand is driven by gas demand. Figure 7 provides the sectoral demand for natural gas from the EUCO30 scenario for years 2030 and 2050, along with the 2015 demand from JRC-IDEES[2] data.

In EUCO30 for year 2050, the European Union's gas demand breaks down in 69 TWh for transport, 905 TWh for industry and 945 TWh for other uses excluding gas for power generation. To decarbonise the gas sector, these CH_4 demands could be partially replaced by (carbon-neutral) synthetic CH_4 produced using power-to-CH_4.

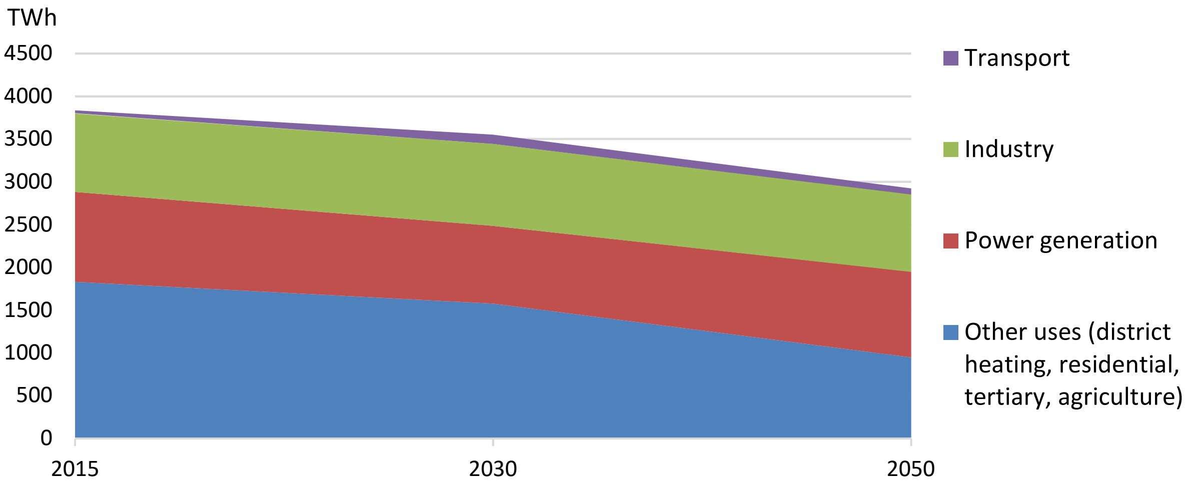


Figure 7 - Potential demand for CH_4 in European Union under the EUCO30 scenario for year 2030 and 2050. 2015 data are from JRC-IDEES.

[2] "Integrated Database of the European Energy Sector" from the Joint Research Center, the European Commission's science and knowledge service

4.1.3. POTENTIAL DEMAND FOR POWER-TO-LIQUIDS

As power-to-Liquids products are substitutes of fossil liquids, the potential demand for power-to-Liquids products can be assessed thus by the need for fossil liquids. EUCO30 scenario also provides fossil liquids demands for year 2030 and 2050 which are reported on Figure 8. The transport sector holds the largest share of fossil liquids with almost 95% of the total energy use demand[3].

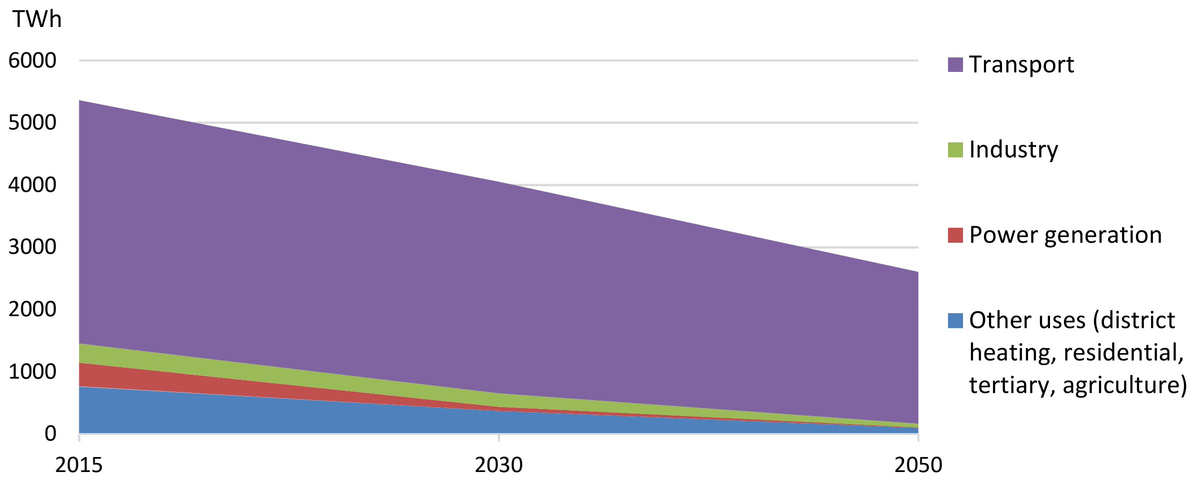


Figure 8 - Potential demand for liquids in European Union under the EUCO30 scenario for year 2030 and 2050. 2015 data are from IDEES.

4.1.4. OVERVIEW OF POWER-TO-X POTENTIAL DEMAND

Table 2 sums up the potential annual volumes for power-to-X in 2050 as provided by the literature survey. As expected, 2050 H_2 demand for transport and other end-use sectors (residential, tertiary, agriculture) are clearly lower than demands for other power-to-X products. However, a high hydrogen demand can be projected for the industry sector in 2050.

Table 2 - 2050 potential demand for power-to-X products (in TWh)

Sector	H_2 **demand**	CH_4 **demand**	**Liquids demand**
Industry	> 500 TWh	900 TWh	60 TWh
Transport	100 TWh	70 TWh	2430 TWh
Other uses (excluding power generation and non-energy use)	*Gas grid injection: few % of CH_4 demand*	950 TWh	100 TWh

[3] Only liquid demand for energy use is considered here which do not match with the total liquid demand. Indeed, a non-negligible volume of liquids is used for non-energy purpose (16% of the EU final consumption of liquids is non-energy use (IDEES)).

4.2. POWER-TO-H_2 TECHNOLOGIES

This section describes different technologies of hydrogen production, starting with power-to-H_2 technologies (i.e. different kinds of water electrolysis, cf. Section 4.2.1), and subsequently explaining conventional technologies (cf. Section 4.2.2).

4.2.1. TECHNICAL AND ECONOMIC PARAMETERS

Power-to-H_2 characterises the process of generation synthetic H_2 by using electricity. Water electrolysis is currently the main technique to achieve this process: H_2O is decomposed into H_2 and O_2 by using electric power. In the remaining part of this report, power-to-H_2 only refers to water electrolysis.

To produce H_2, three technologies can be distinguished: alkaline electrolysis, proton exchange membrane electrolysis (PEM) and solid oxide electrolyser cell (SOEC). Each one of them is detailed below. Moreover, all three technologies – and especially SOEC – could be upgraded by running the electrolysis process at high – rather than low - temperatures, thereby enhancing the process efficiency. However, because high temperature electrolysis and SOEC are currently not mature, literature does not provide technical and economic data projections for these technologies. As a consequence, low temperature alkaline and PEM are the only two technologies whose data have been analysed in details for power-to-H_2 (see below).

The H_2 production costs depend on four key parameters: lifetime, energy conversion efficiency, capital expenditures (CAPEX) and operating expenses (OPEX). They are explained in more detail in the factsheets below [2, 15, 16, 17].

ALKALINE ELECTROLYSIS

- The following reactions take place:
  - Anode: $2\,OH^- \rightarrow {}^1/_2\,O_2 + H_2O + 2e^-$
  - Cathode: $2\,H_2O + 2e^- \rightarrow H_2 + 2\,OH^-$
- Pressure of hydrogen delivered: 0.05 to 40 bars
- Operating temperature: 60 to 80°C
- Hydrogen purity: 99.5 % before purification, > 99.999% after the purification unit
- Start-up time: ~20min for cold start-up
- Flexibility: few seconds for ramp-up and ramp-down from minimum load to maximal load (or conversely): 13 to 20 % of full-load / seconds

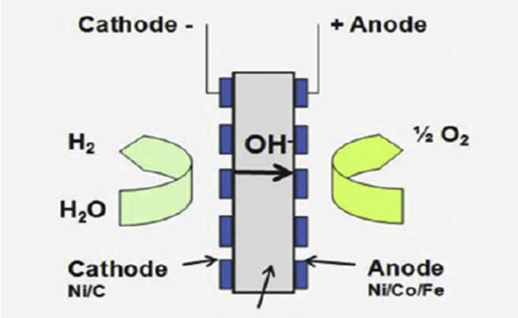
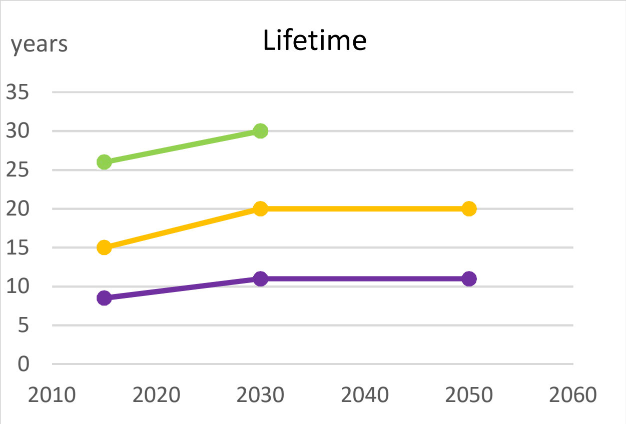
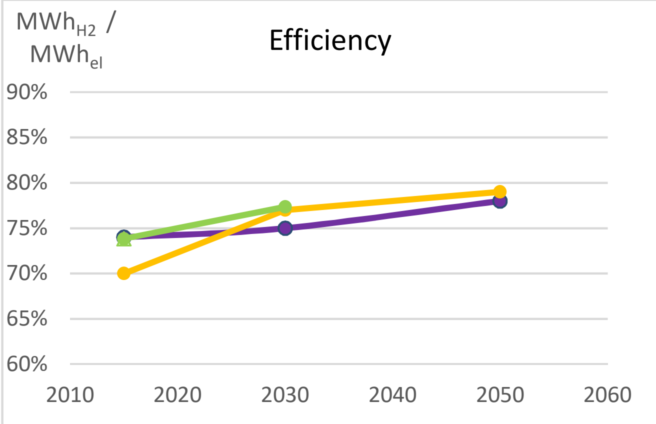
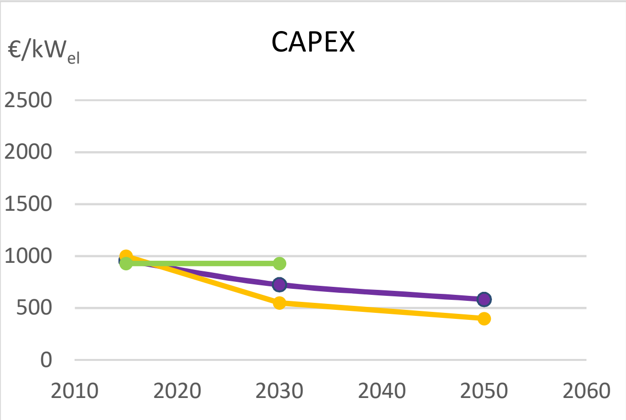


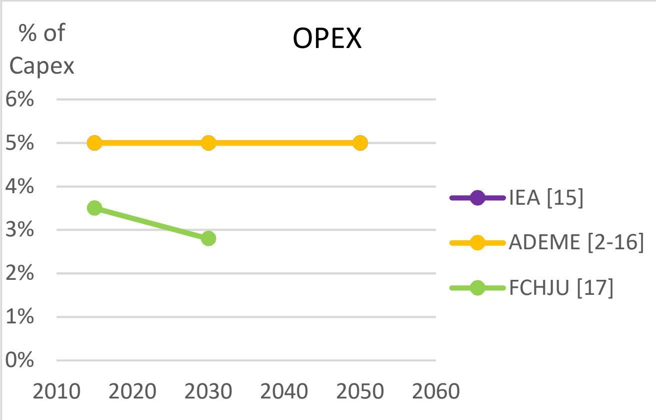
Figure 9 - Illustration of the operating principle of an alkaline water electrolysis cell [31]

KEY PARAMETERS









TECHNICAL ADVANTAGES

- Currently the cheapest electrolysis technology
- Fast response time enables the provision of power system services (i.e. flexibility)
- Longer lifetime than PEM
- High hydrogen purity (some consumers have high purity quality standards, such as the transport sector[4])

DRAWBACKS

- Low margin of improvement on CAPEX
- Hazardous corrosive electrolyte

[4] ISO 14687

PEM ELECTROLYSIS

- The following reactions take place:
  - Anode: $2\,H_2O \rightarrow O_2 + 4H^+ + 4e^-$
  - Cathode: $2H^+ + 2e^- \rightarrow H_2$

- Pressure of hydrogen delivered: 20 to 80 bars
- Operating temperature: 60 to 80°C
- Hydrogen purity: 99.95 % before purification,
  > 99.998% after the purification unit
- Start-up time: 5 to 15 min for cold start-up
- Flexibility: few seconds for ramp-up and ramp-down from minimum load to maximal load (or inversely): 10 to 100 % of full-load / seconds

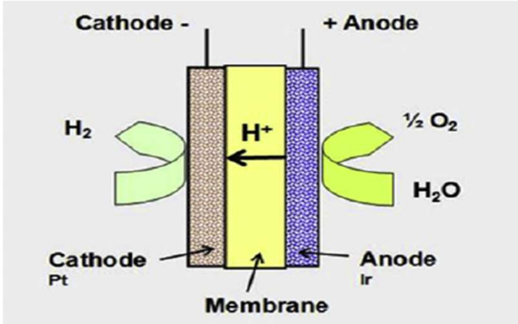


Figure 10 - Illustration of the operating principle of a PEM water electrolysis cell [31]

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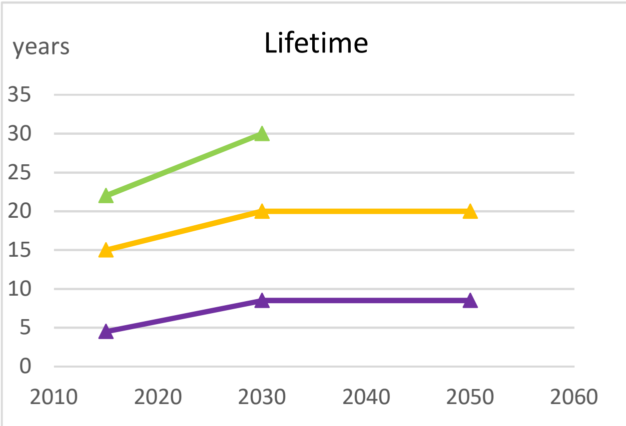
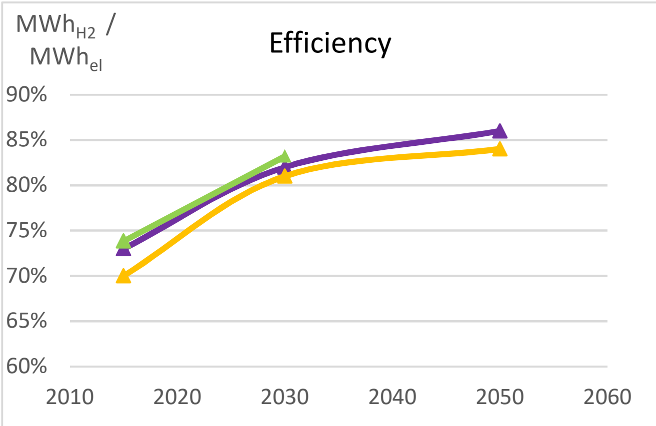
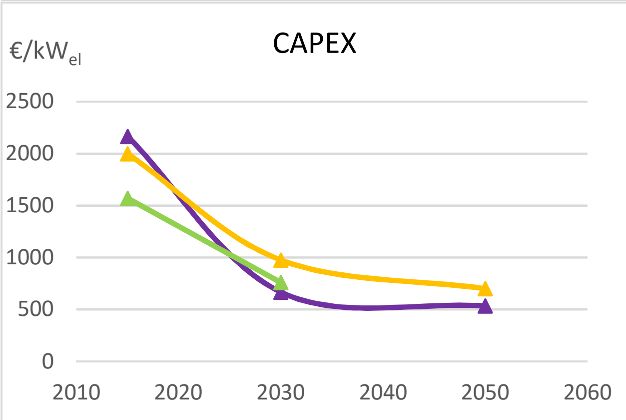
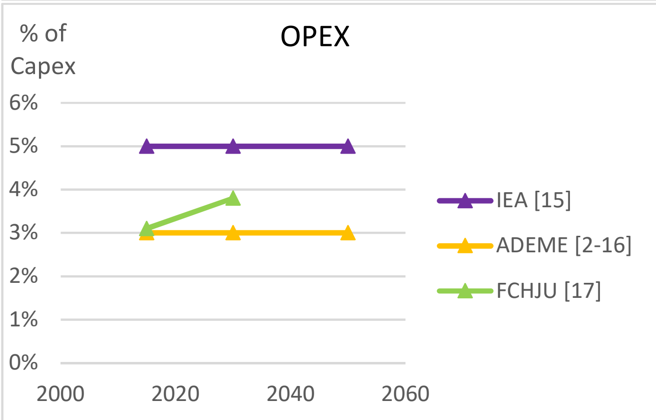








TECHNICAL ADVANTAGES

- Absence of electrolyte enables to operate easily the technology compared to alkaline
- Compactness, easiness of fabrication
- Less influence from inlet conditions
- Fast response time to flexibility
- High hydrogen purity

DRAWBACKS

- Use of precious metals (cost dependence)
- Less mature than alkaline technology: not commercial at large scale yet (higher CAPEX)

SOEC ELECTROLYSIS

- The following reactions take place:
  - Anode: $2\,O^{2-} \rightarrow O_2 + 4e^-$
  - Cathode: $2H_2O + 4e^- \rightarrow 2H_2 + 2\,O^{2-}$
- Operating temperature: 600 to 1000°C
- Key parameters in 2050 [2] [6] [16]:
  Efficiency: 80% to 100%
  Lifetime: 15 to 20 years
  CAPEX: 1000 to 1200 €/kW$_{el}$
  OPEX: 3 to 3.5% of CAPEX

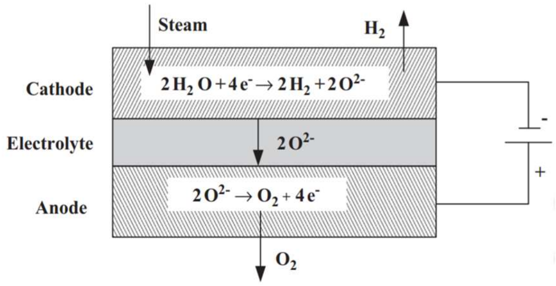


Figure 11 - Illustration of the operating principle of SOEC [32]

TECHNICAL ADVANTAGES

- Better efficiency than other technologies
- Can be coupled with other processes for heat recovery at low cost

DRAWBACKS

- Far from commercial
- Less flexible than others technologies and unsuitable to intermittent running [16]

4.2.2. H_2 PRODUCTION BENCHMARK

Besides the water electrolysis, H_2 can be produced by alternative techniques such as:

- Steam reforming of natural gas, also known as Steam Methane Reforming (SMR)
- Partial oxidation of fossil energy
- Autothermic reforming: combination of steam reforming and partial oxidation
- Coal gasification
- Biomass gasification
- Thermochemical cycles
- Photocatalytic water splitting
- Photo-biological water splitting
- Coproduct of acetylene and olefins production, or refineries

Currently, hydrogen production is almost exclusively fossil-fuel based (96% of the total hydrogen production), with SMR as the main provider (48%). Catalytic reforming used in petroleum refineries (hydrogen is a side-product of oil processing) is the second hydrogen producer (30%), followed by coal gasification (18%).

SMR decomposes natural gas into hydrogen and CO_2. Consequently, SMR has the inconvenient to be very carbon-intensive (0.23 tons of CO_2 per MWh of H_2 produced). To secure H_2 production while decreasing CO_2 emissions, a Carbone Capture and Storage (CCS) facility can be added to the SMR plant.

Under the assumption of a high decarbonisation rate in the gas sector, and given current technological trends, the main competitor for power-to-H_2 would be SMR with CCS, which is detailed in the factsheet below.

SMR / SMR + CCS

SMR method:

- Firstly, the following reaction take place:

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO$$

- Then, elimination of CO via high temperature or low temperature Water Gas Shift:

$$CO + H_2O \leftrightarrow H_2 + CO_2$$

The resulting mix is $H_2 + CH4 + H_2O + CO_2$

- Purification via Pressure Swing Adsorption (PSA)

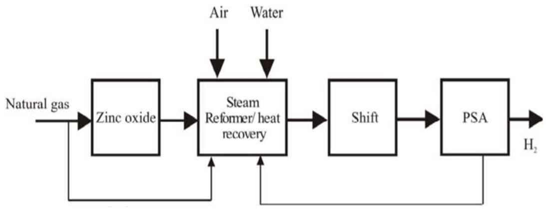
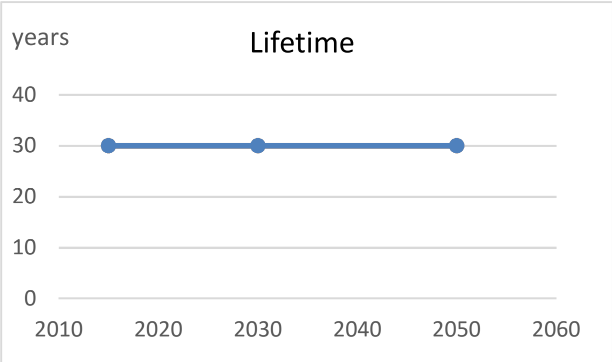
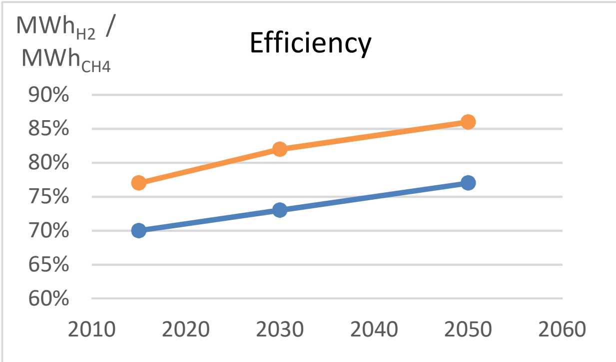
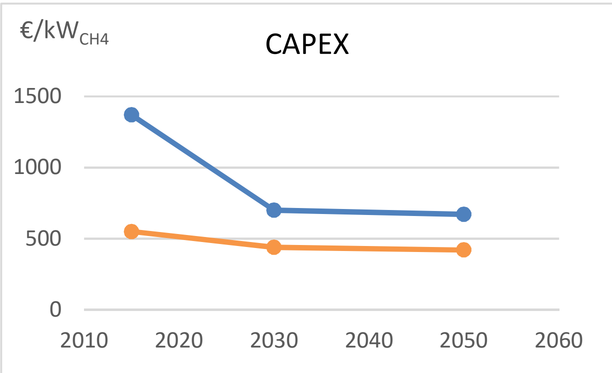


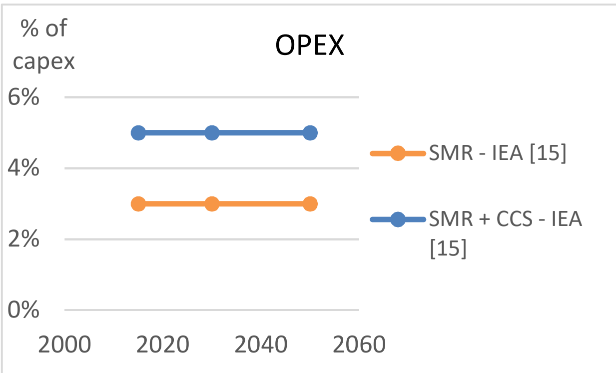
Figure 12- Block flow diagram of hydrogen via steam methane reforming [29]

KEY PARAMETERS









TECHNICAL ADVANTAGES

- SMR offers an efficient, economical, and widely used process for H_2 production

DRAWBACKS

- SMR is sensitive to natural gas price and to CO_2 cost
- CCS is not currently commercially available
- SMR + CCS development depends on CCS progress and its ability to integrate the SMR plant

The SMR+CCS configuration features more important costs (CAPEX and OPEX) than the simple SMR process. However, the CCS component may pay off if the carbon price and the number of full load hours are sufficiently high. In order to determine the break even, the production costs are computed (variable cost + internalised investment cost) for both technologies. The production costs equal the following equations:

$$productionCost(SMR) = \frac{annualisedCapex(SMR) + Opex(SMR)}{Load\ hours} + CH_4Cost(SMR) + CO_2Price(SMR)$$

$$productionCost(SMR + CCS) = \frac{annualisedCapex(SMR+CCS) + Opex(SMR+CCS)}{Load\ hours} + CH_4Cost(SMR + CCS)$$

with $annualisedCapex$ depending on CAPEX, lifetime and discount rate. CH_4 cost of 35.27 €/MWh$_{CH4}$ is used (assumption from EUCO30 scenario at horizon 2050) and efficiencies of both technologies are taken into account. While currently ranging from 56% to 90%, an efficiency of 100% is assumed here for 2050.

Moreover, CCS plant is assumed to have a 100% CO_2 capture rate by 2050. According to IEAGHG [18], current technology involve the CO_2 capture rate of a SMR + CCS plant in the range of 56% to 90%. By 2050, a 100% capture rate is a coherent assumption considering the necessary research and development of this technological solution.

Figure 13 depicts the more competitive of the two technologies for a range of CO_2 price and annual utilisation. For high full-load factors, SMR+CCS can be economical with CO_2 prices greater than 50€/tCO_2.

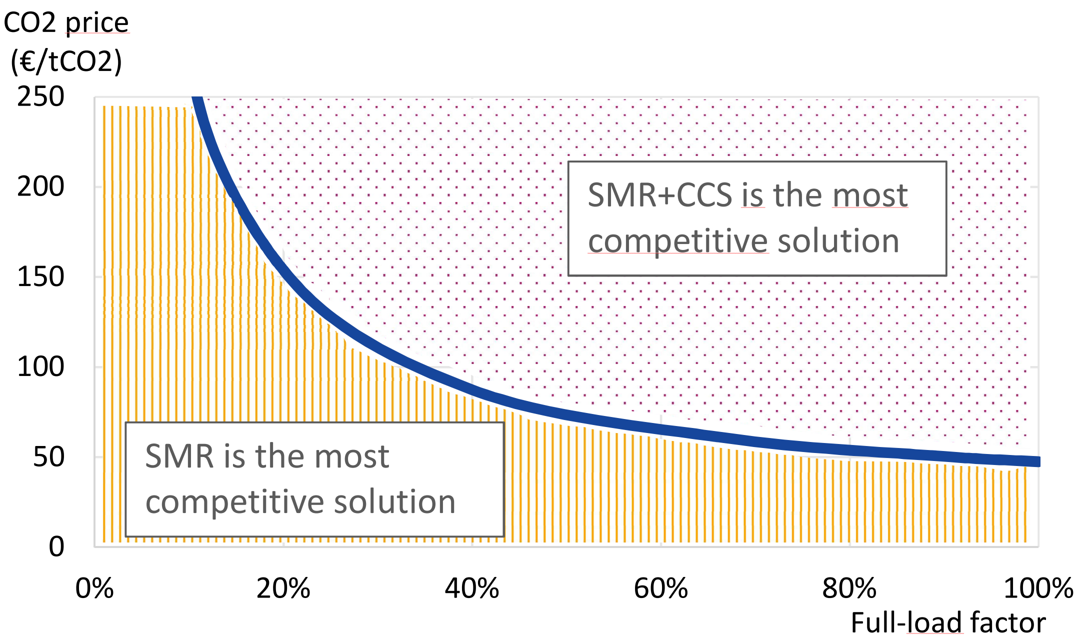


Figure 13 - Comparison between SMR and SMR + CCS under 2050 assumptions

4.3. POWER-TO-CH_4 TECHNOLOGIES

4.3.1. TECHNICAL AND ECONOMIC PARAMETERS

After electrolysis, hydrogen can be converted to methane through a process called methanation. Methanation is the reaction of hydrogen with carbon monoxide (CO) or carbon dioxide (CO_2) to methane. CO methanation has been developed through the 20th century for the process of ammoniac production in order to refine gases containing CO, then in the 70s for coal-to-gas/liquids processes. Recently, this technique has received a renewed interest for the conversion of coal into synthetic gas (USA, China and India) and for biomass conversion into synthetic gas in Europe.

Techniques for methanation of CO_2 is similar to CO methanation thus it can rely on its historic development. CO_2 methanation can be described by the following reaction:

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

It is an exothermic reaction, so it releases heat which can be recovered depending on the type of technique used.

This reaction can happen through two different techniques: catalytic methanation or biological methanation. Catalytic reaction takes places inside a reactor with the presence of a catalyser such as nickel, rhodium or ruthenium, nickel being more often used because of its low cost. Two types of reactors can be used: the adiabatic reactor and the isothermal reactor. There is no heat exchange between the adiabatic reactor and the reaction fluids which results in an increase of the temperature inside the reactor. Isothermal reactor includes a cooling circuit allowing to eject heat and to control temperature inside reactor. Temperature control is important in order to ensure the best feasible efficiency rate and kinetic of reaction.

Biological way is an emerging technology using methanogenic microorganisms operating as bio-catalysts. The reaction takes place under anaerobic conditions inside a so-called digester where there are two possibilities of process. Either H_2 is directly added to CO_2 initially stored inside digester with microorganisms, or H_2 is firstly mixed with CO_2 then the aggregated gas is sent to the digester filled with water containing the microorganisms. Biological methanation has two main issues: adding hydrogen increases the pH of the liquid phase inside reactor which can inhibit methane production, and the gas/liquid interface of the reaction medium (water with microorganism is a liquid whereas hydrogen is gaseous) is a strong barrier for mass transfer and limit effective kinetic of the reaction.

The major technological information about both methanation processes are summarised in the factsheets below. Because catalytic methanation is the most mature technology and because projection data in 2050 for technical and economic parameters are more exhaustive for catalytic methanation, this study only analyses the catalytic way.

Both methanation processes need a reliable CO_2 source. Description of the different CO_2 sources as well as their associated capture costs can be found in section 4.5.

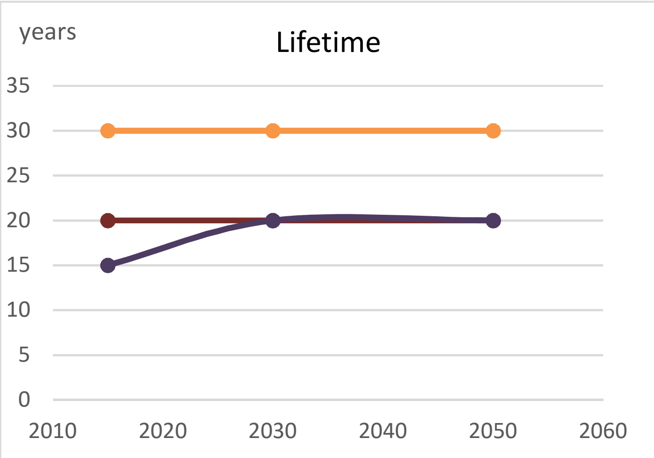
CATALYTIC METHANATION

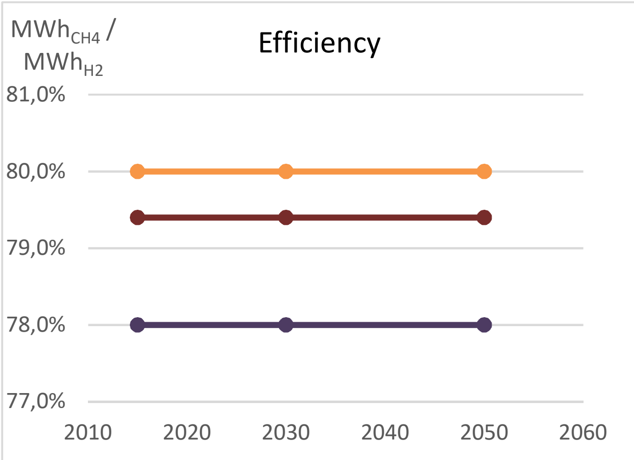
- Reaction inside the reactor:

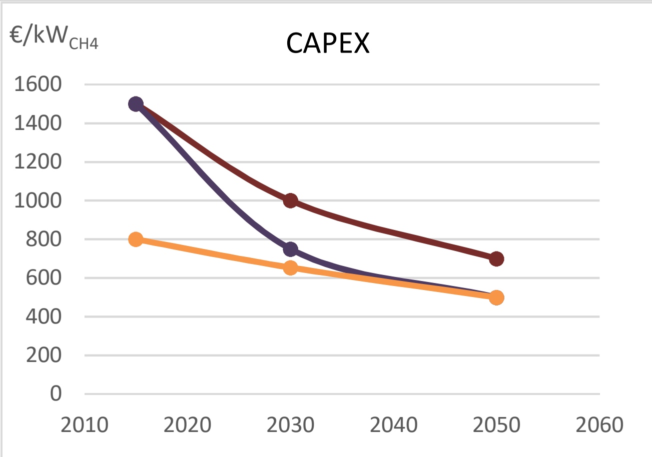
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

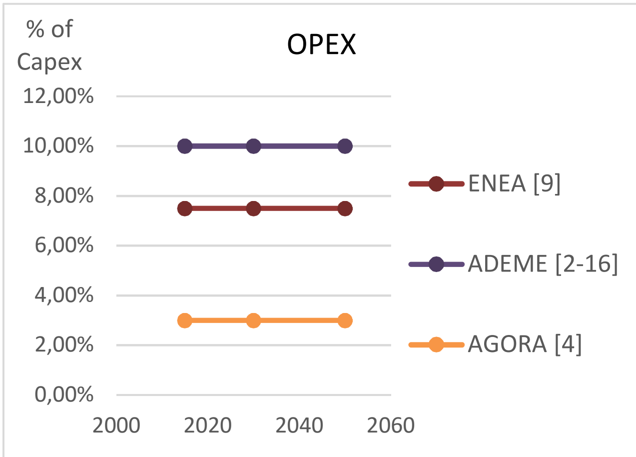
- Operating pressure: up to 10 bars
- Operating temperature: around 450°C
- Methane rate in outlet gas: up to 92%
- Flexibility: response time ~ 1 minute

KEY PARAMETERS









TECHNICAL ADVANTAGES

- Technology well-known from the industry
- Efficiency can be improved by recovering high temperature heat liberated during the reaction

DRAWBACKS

- Need a temperature control inside the reactor: a high temperature can damage the catalyser
- Longer response time than electrolysis: a buffer tank might be necessary

BIOLOGICAL METHANATION
• Operating temperature: between 35°C and 65°C depending on type of microorganisms • Operating pressure: atmospheric pressure (1 bar) • Methane rate in outlet gas: 98-99% • Efficiency: 78-80% ($MWh_{CH4\ HHV}$ / $MWh_{H2\ HHV}$$H_2$ HHV) • CAPEX: 1000 €/kW_{CH4} • OPEX: ~12% (capex) • Flexibility: ramp-up time from 0 to 90%: ~second/minutes
TECHNICAL ADVANTAGES
• Simple technology • No catalyser • High purity of outlet methane • Better response time than catalytic methanation • Raw biogas can be use as CO_2 source (depend on type of digester) • Important cost reductions are foresight by professionals in next decades
DRAWBACKS
• Not a mature technology yet • pH control inside the digester

4.3.2. CH_4 PRODUCTION BENCHMARK

CH_4 production is currently dominated by fossil natural gas, with only a small portion coming from biogas. Biogas refers to a mixture of different gases produced by the breakdown of organic material (biomass), mainly CH_4 and CO_2, and secondarily H_2, O_2, H_2S (hydrogen sulphide) and N_2 (nitrogen). In the European Union in 2015, natural gas consumption has reached about 4 160 TWh whereas biogas consumption was around 182 TWh which represents 4% of total consumption. After further purification, the biogas becomes biomethane which have the same quality as natural gas and whose production has significantly increased in the past years. Contrarily to biogas, biomethane has the ability to be used in vehicles and to be injected in the gas grid. The overall injection rate of biomethane into the gas grid at the EU level is difficult to estimate, but for example in France in 2017, about 406 GWh of biomethane has been injected into the grid compared to an overall gas demand of 466 TWh (0.87 ‰).

Biomass-to-CH_4 (biomethane) has two main production techniques: anaerobic digestion and thermal gasification. Similar to biological methanation, anaerobic digestion performs a series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. The process results in a digestate and biogas (CH_4 and CO_2 mainly). In order to obtain biomethane, the biogas needs to be upgraded to methane by removing CO_2 (via the so-called purification process). A schematic overview of anaerobic digestion is shown in Figure 14.

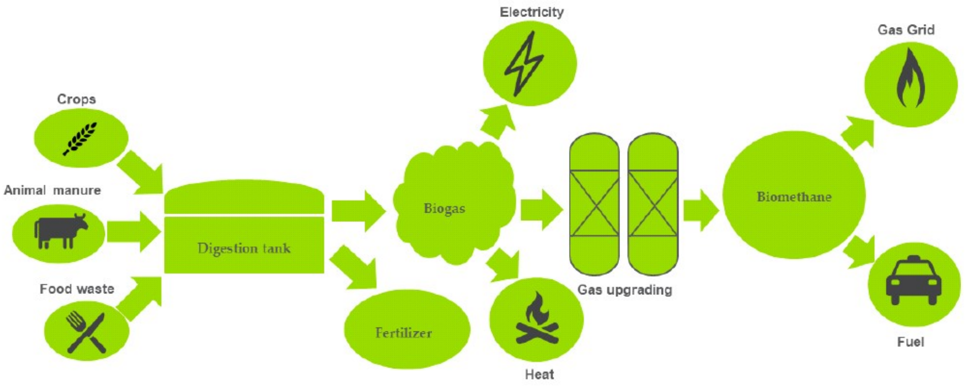


Figure 14 - Schematic overview of the anaerobic digestion process [19]

In thermal gasification, a thermal breakdown of woody biomass and consumer wastes takes place in a gasifier, in the presence of a controlled amount of oxygen and steam. The resulting syngas (containing CO, CO_2, H_2 plus pollutants like sulphur and chlorides) is cleaned and upgraded to biomethane thanks to a methanation unit (like catalytic methanation for power-to-CH_4). A schematic overview of thermal gasification is presented in Figure 15.

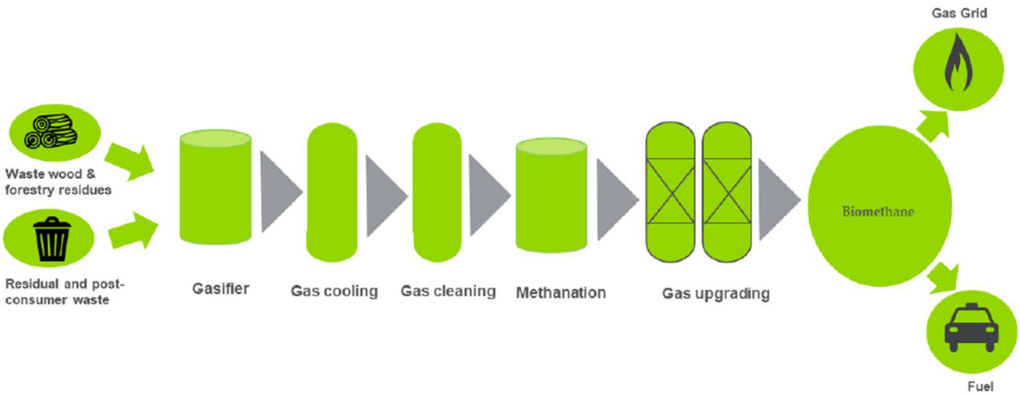


Figure 15 - Schematic overview of the thermal gasification process [19]

Like for the H_2 production, the main competitor for power-to-CH_4 production has to be assessed. Assuming a high CO_2 price, it is likely that power-to-CH_4 would need to compete with biomass-to-CH_4 as carbon-neutral alternative. Moreover, both CH_4 production chains feature nearly the same CH_4 purity at the outlet of the production processes, allowing both CH_4 products to be directly injected into the gas grid.

In order to sound assessment of the competitiveness of power-to-CH_4 by 2050 in comparison to biomethane, the production costs of the latter need to be estimated. For this purpose, a literature survey has been realised, based on the following public reports and data sources:

- Un mix de gaz 100% renouvelable en 2050, ADEME (2018) [2]
- Biogas for Road Vehicles, Technology brief, IRENA (2017) [20]
- Etat des lieux du biométhane en France, ENEA (2017) [21]
- Biomass for power generation, Renewable Energy Technologies: Cost Analysis Series, IRENA (2012) [22]
- BioMethane in Transport, EBA (2016) [23]
- Biofuels for aviation, IRENA (2017) [24]

This review reveals a large spread of production costs for the years 2015 and 2050 (cf. Figure 16). This spread is mainly due to the cost difference between anaerobic digestion and gasification, and to the difference between feedstock costs (different organic raw material).

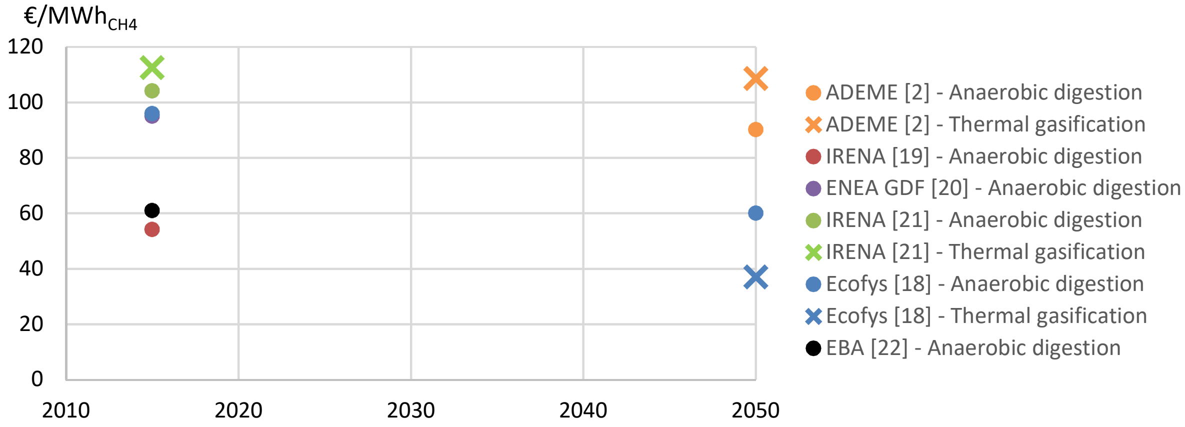


Figure 16 - Literature survey for the current value and projection of biomethane production cost.

4.4. POWER-TO-LIQUIDS TECHNOLOGIES

4.4.1. *TECHNICAL AND ECONOMIC PARAMETERS*

Following the water electrolysis process, synthetic hydrogen can be converted into different liquid fuels such as diesel/gasoil-like fuels, ethanol, methanol, dimethyl ether or ammoniac. Each liquid has its own conversion process. In the remainder of the report, the focus is set on diesel/gasoil-like fuels generated via the power-to-Liquids process chains, for two major reasons. First, these fuels are produced via Fischer-Tropsch synthesis or via methanol synthesis which are the most experimented power-to-Liquids processes and hence feature the highest data availability with respect to technical and economic parameters. Second, these fuels are likely to experience an important utilisation in the future because of their ability to replace fossil fuels in specific segments of the transport sector where battery electric or fuel cells can be employed only to a limited degree, such as aviation.

Details about liquid fuels production via Fischer-Tropsch synthesis or via methanol synthesis is given below. Compared to the literature on methanation and even more on hydrogen electrolysis, power-to-Liquids are not yet that well documented and thus only few projections of key parameters until the year 2050 are available. In the following, parameters of both technologies are reported but only Fischer-Tropsch synthesis is considered in the uses case construction. This choice is motivated by the power-to-Liquids competition that is analysed in Section 4.4.2 and that corresponds to advanced Bio-fuels which can be directly used in internal combustion engines (ICEs). Moreover, the first power-to-Liquids plants that are currently planned and built make use of the Fischer-Tropsch process (for example *Nordic Blue Crude* in Norway or *Sunfire* in Germany).

Both Fischer-Tropsch and methanol syntheses need a reliable CO_2 source. Section 4.5 presents the different CO_2 sources as well as their associated capture costs.

LIQUID FUELS PRODUCTION VIA FISCHER-TROPSCH SYNTHESIS

Fischer-Tropsch process produce a variety of hydrocarbons through the main reaction:
$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$
with n typically 10-20, resulting in a raw liquid fuel that is refined.

Other minority reactions take place inside the reactors.

The carbon monoxide is obtained from carbon dioxide using a reverse water-gas shift reaction.

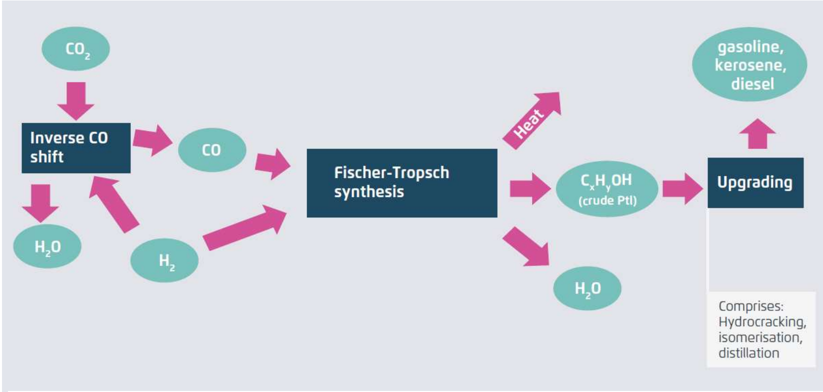
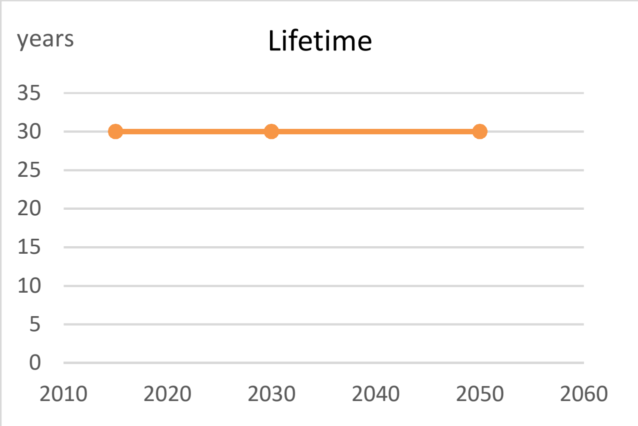
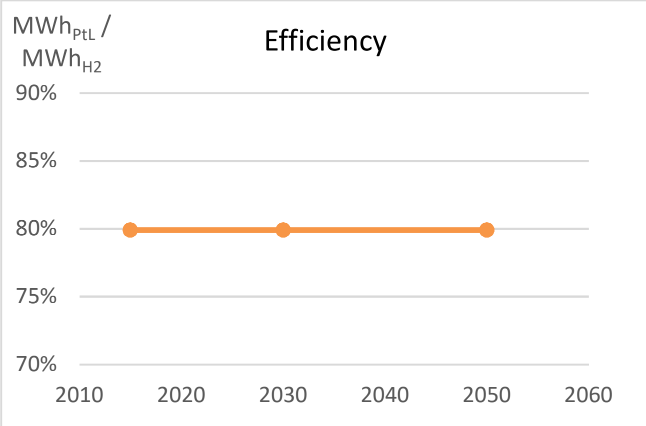
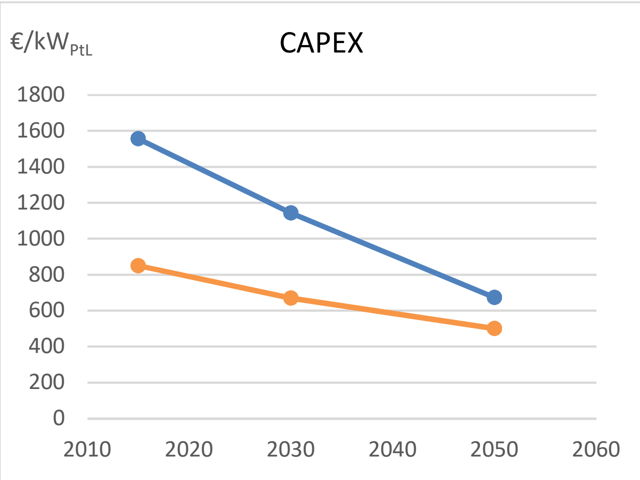


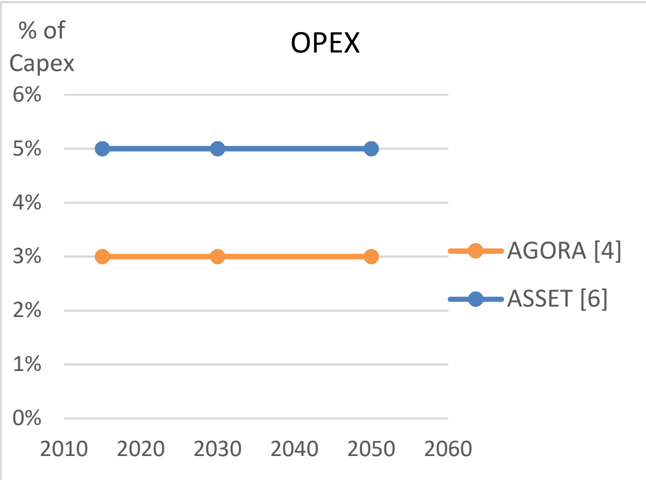
Figure 17 – Schematic overview of liquid fuel production via Fischer-Tropsch synthesis [4]

KEY PARAMETERS









TECHNICAL ADVANTAGES

- Relatively established technology because it is already used for coal-to-Liquids processes [4]

DRAWBACKS

- Not yet fully mature for power-to-Liquids processes

FUELS PRODUCTION VIA METHANOL SYNTHESIS

Methanol synthesis reaction:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

if $\mathrm{CO_2}$ flow is available. Methanol can be also produced by reaction between $\mathrm{H_2}$ and CO.

Methanol can be upgraded by further conversion to synthetic petrol, diesel or monomolecular fuels such as OME (oxymethylene ether) or DME (dimethyl ether).

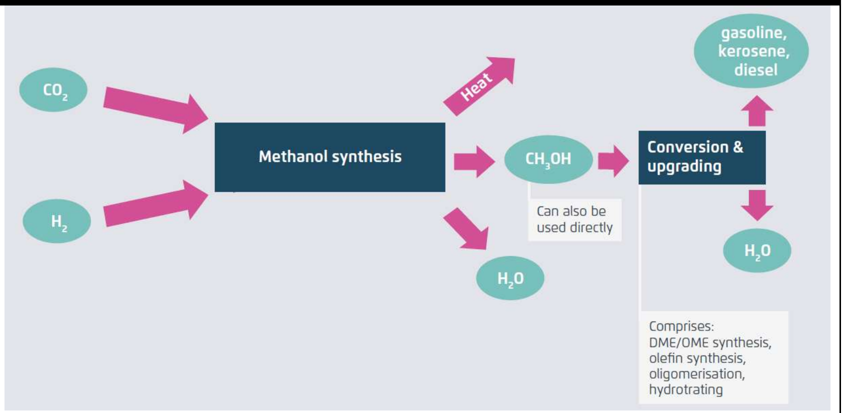
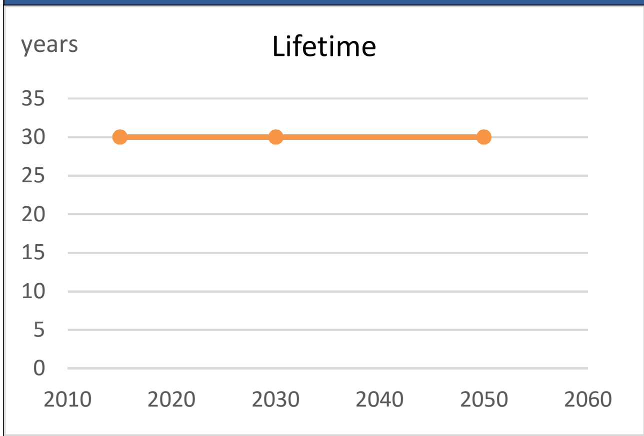
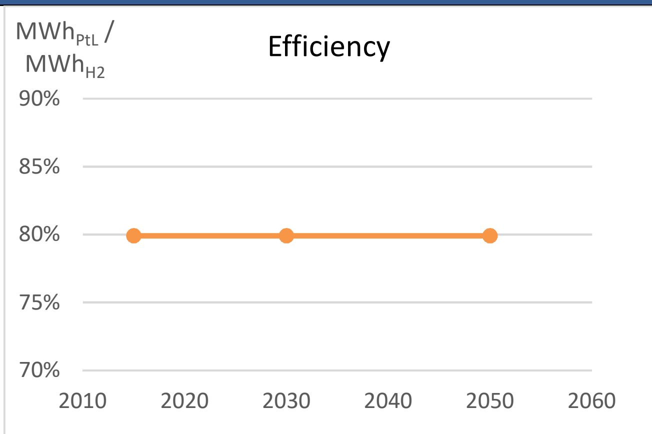
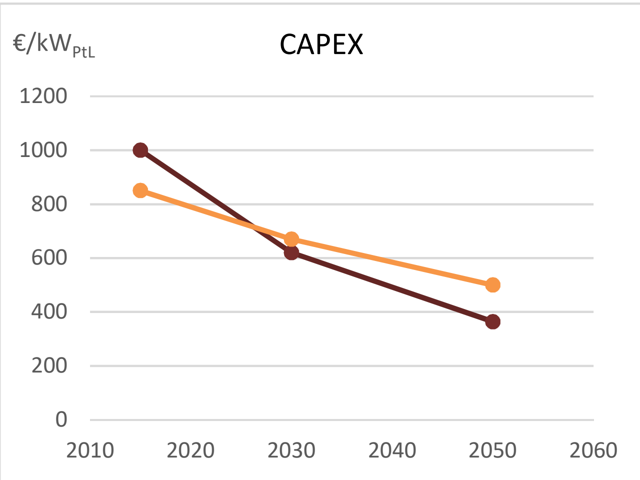


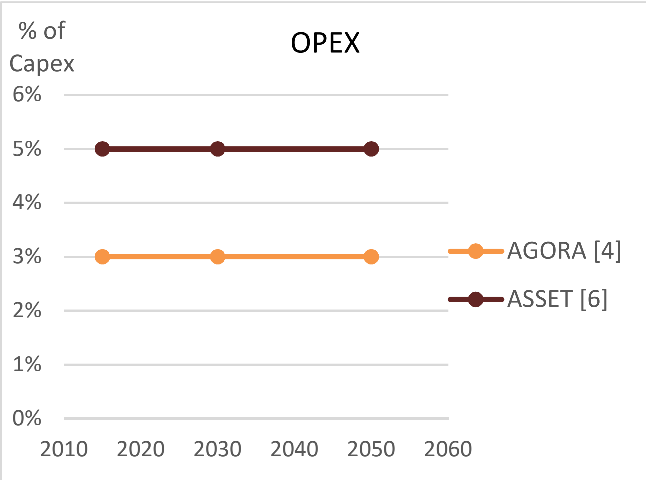
Figure 18 - Schematic overview of liquid fuel production via methanol synthesis [4]

KEY PARAMETERS









TECHNICAL ADVANTAGES

- Methanol synthesis is a known process but feedstocks are natural gas or coal

DRAWBACKS

- Not currently mature for power-to-Liquids processes

4.4.2. FUELS PRODUCTION BENCHMARK

To evaluate power-to-Liquids competition at the 2050 horizon, biofuels technology has been chosen as benchmark for several reasons. First, both technologies being carbon-neutral over a full cycle, they are not subjected to the CO2 pricing. Further, biofuels are expected to take up in the following years, led by current and future biofuels standards in EU, Brazil, China and US (for example, the EU Renewable Energy Directive rules that all EU countries must ensure that at least 10% of their transport fuels come from renewable sources by 2020 [25]). In 2050, biofuels could represent an important part of transport fuel production worldwide: up to 27% according to IEA projection [26].

Biofuels can be considered as the most developed sub-category of the biomass-to-Liquids technologies. Among biofuels technologies, first-generation biodiesel[5] and bioethanol currently are the most developed ones, but they have a limited growth because of their competition with the food industry and their limited benefits in terms of CO_2 emissions[6]. Therefore, only advanced biofuels - especially advanced biodiesel - production cost has been investigated to estimate power-to-Liquids competition in 2050. IEA [26] terminology defines advanced biodiesel as a second- or third-generation biodiesel which can be entirely used in ICEs (not only blending). Considering advanced biodiesel as the main competitor for power-to-Liquids appears to be all the more relevant as power-to-Liquids fuels do not need blending with another fuel either (they can be directly used in ICE). Figure 19 provides current projections for advanced biodiesel production costs[7].

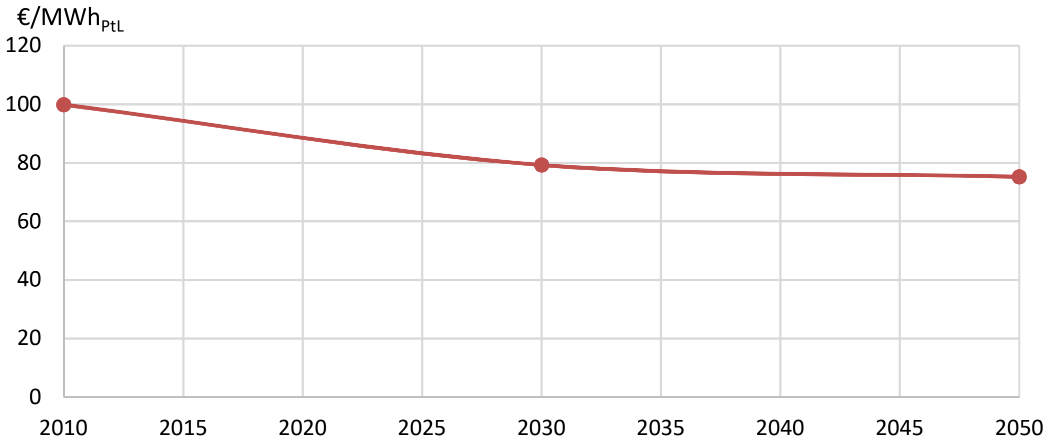


Figure 19 - Literature survey for the current value and projection of advanced biofuels production cost. Source: IEA [26]

4.5. CO_2 CAPTURE

Many power-to-X technologies depend on a reliable source of CO_2 for chemical conversion of hydrogen into methane or liquids, as described previously. Three sources of CO_2 supply exist, each one having distinct advantages and drawbacks. The main criterion is the cost of capture. A cost comparison between the three technologies is shown in Figure 20.

- **Direct Air Capture**

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[5] First-generation biofuels refer to fuels that have been derived from food crops which make them compete with food production. Second- and third-generation biofuels use non-food resources. This categorisation matches to current biofuels (first generation) and future biofuels (second generation) used by EU's policy: see EU Fuel Quality Directive [13] for further details.

[6] Since they induce deforestation

[7] Advanced biofuels costs will however depend on the general level of development of bioenergy.

Capturing CO_2 directly from the atmosphere has the advantage to be completely independent from any other artificial CO_2 source (i.e. industrial or power plant). This technology to capture CO_2 further has the advantage to remove emissions that were emitted in the past through various (potentially decentralised) CO_2 sources such as transport or individual boilers. However, it is also the most expensive way to capture CO_2, nowadays as well as in the long-run because of the relatively low CO_2 concentration in the atmosphere. Although literature questions the credibility of this solution [16], some companies develop their own products applying this technology (for example *Climeworks* or *Skytree*).

- **Capture from biomass**
  As explained previously, digestion or gasification processes produce biogas which is containing CO_2. After anaerobic digestion, purification units can provide pure CO_2 (see Figure 14).

- **Capture from industry**
  A lot of different industries produce CO_2 with different CO_2 concentrations. Hydrogen and ammoniac produce very highly concentrated (almost pure) CO_2 flows but these sources are expected to gradually disappear with the rising diffusion of power-to-X applications. Other industries emitting recoverable CO_2 include blast furnaces (cement plants for example) or coal or gas boilers (in thermal power plants or industrial steam and heat generation processes). CO_2 is diluted in exhaust gasses and thus needs to be separated from other chemical components. Yet, in the long run carbon emissions from the power sector are expected to completely disappear (due to decarbonisation targets) and thus power plants do not represent a reliable CO_2 source. Thus, CO_2 capture for the combination with power-to-X processes should rather focus on other types of industries [16]. Different technologies are emerging for CO_2 capture such as absorption process, adsorption process, membrane uses or oxycombustion (see [27] for further details on CO_2 capture technologies).

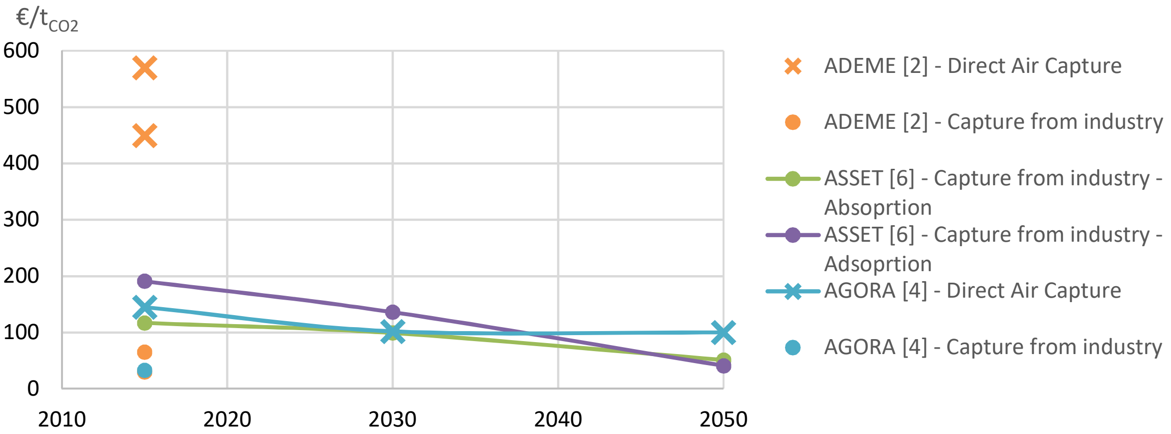


Figure 20 - Literature survey for the current value and projection of CO_2 capture costs. Plain dots stand for capture from industry whereas crosses represent direct air capture.

In terms of potential, Direct Air Capture seems to be the most promising technology because it can be installed everywhere and the theoretical potential volume is infinite. Nevertheless, this technology remains expensive at the time of writing this report thus current project would rather use industrial capture if a CO_2 emitting industry is available. However, at the horizon 2050, both technologies are assumed to have more of less the same capture cost. Direct Air Capture could have a significant role in 2050 if capture costs decrease.

5. METHODOLOGY AND DEFINITION OF USE CASES

This section describes the methodology used to assess the competitiveness of each power-to-X technology, compared to their respective competitor. A marginal approach is used (cf. Section 5.1) to identify a threshold electricity price (cf. Section 5.2) under which power-to-X would be competitive. This method is applied on different use cases introduced in Sections 5.3, 5.4 and 5.5, reflecting different power-to-X technologies and energy usages.

5.1. MARGINAL APPROACH

This study aims at analysing under which economic conditions a spontaneous development of power-to-X business cases could be triggered. The methodology consists in assessing the profitability of 1 MW of power-to-X capacity in the METIS EUCO30 2050 scenario. Since the original scenario does not include power-to-X capacities, it is important to note that the results presented in this report can only be interpreted as the potential profitability of the *first* MW of a given power-to-X technology in this scenario.

Indeed, a comprehensive power-to-X development would have significant impacts on the power system. For example, an assumption of a high decarbonisation of the transport sector would be likely to lead to an increase in demand for hydrogen from power-to-H_2 or synthetic fuels from power-to-Liquids (as fossil fuels substitute). Such extra demands would imply a need for additional power generation capacity. Moreover, in a high decarbonisation context of the gas system, injection of synthetic gasses from power-to-H_2 and power-to-CH_4 in the gas grid and the storage potential of power-to-gas-to-power would also have important impacts on the power system. These effects are captured in a separate analysis that is realised in the framework of the METIS study S1 on synergies between energy systems.

The marginal approach has yet the advantage to assess under which conditions (namely, the electricity price structure but also the market value of generated gas or liquid and power-to-X CAPEX) the development of the first power-to-X projects can be profitable in a given power mix scenario. When increasing the power-to-X capacity, or involving competitions between different power-to-X technologies, the project profitability could decrease.

Different configurations are considered. Each one of them reflects the competition between one power-to-X technology with an already proven alternative, assumed to set market prices for the generated gas or liquid. The three cases of competition between one power-to-X technology and its main alternative are the following[8]:

- Power-to-H_2 and SMR + CCS
- Power-to-CH_4 and biomass-to-CH_4
- Power-to-Liquids and biomass-to-Liquids (advanced biofuels)

5.2. THE THRESHOLD ELECTRICITY PRICE: A KEY PARAMETER FOR POWER-TO-X PRODUCTION

For each use case, the production costs of the power-to-X technology is contrasted with those of the competing technology, assumed to set the market price. A threshold electricity price is defined as the electricity price equalling power-to-X technology variable cost with the competing technology variable cost (that is the gas/liquid market price). The threshold electricity price can be understood as a willingness-to-pay electricity price under which

[8] The reader may refer to section 4 where the rationale behind each use case is explained.

running existing power-to-X capacity becomes *competitive* with running existing competing technology capacity:

- The product X is produced through power-to-X if:

$$productionCost(PowerToX) \leq productionCost(BenchmarkTechnology)$$

- Production cost of the power-to-X technology depends on the electricity price, on its efficiency and on additional variable costs (such as CO_2 capture cost for power-to-CH_4 and power-to-Liquids):

$$productionCost(PowerToX) = function(parameters(PowerToX), electrityPrice, additionalCost)$$

- From the two previous equations, one can derive a threshold electricity price. The power-to-X technology is competitive at time step t if the electricity price at time t is below the threshold price:

$$electricityPrice(t) \leq thresholdPrice$$

Comparing the electricity price time series with the threshold price, one can determine the full-load hours (FLH) that the first MW of power-to-X technology would have if introduced in the considered power system scenario:

$$FLH = \sum_t \Delta t \,.\, \delta(t)$$

with Δt the time step duration and $\delta(t) = \begin{cases} 1 \text{ } if \text{ } electricityPrice(t) \leq thresholdPrice \\ 0 \text{ } else \end{cases}$.

The profitability of the power-to-X technology is assessed in a second stage, by comparing revenues to fixed costs. (CAPEX and fixed operating costs). As the power-to-X technology only generates revenues when the electricity price drops below the threshold price, the yearly revenues are equal to the cumulated difference between both in all hours when the previous condition is met:

$$yearlyRevenue = \sum_t \big(thresholdPrice - electricityPrice(t)\big).\Delta t \,.\, \delta(t)$$

Besides, all CAPEX and fixed OPEX are annualised over the technology's lifetime (in €/MW/year):

$$annualisedInvestment = annualisedCapex + Opex$$

$$annualisedCapex = \frac{Capex\,.r}{(1 - \left(\frac{1}{1+r}\right)^T)}$$

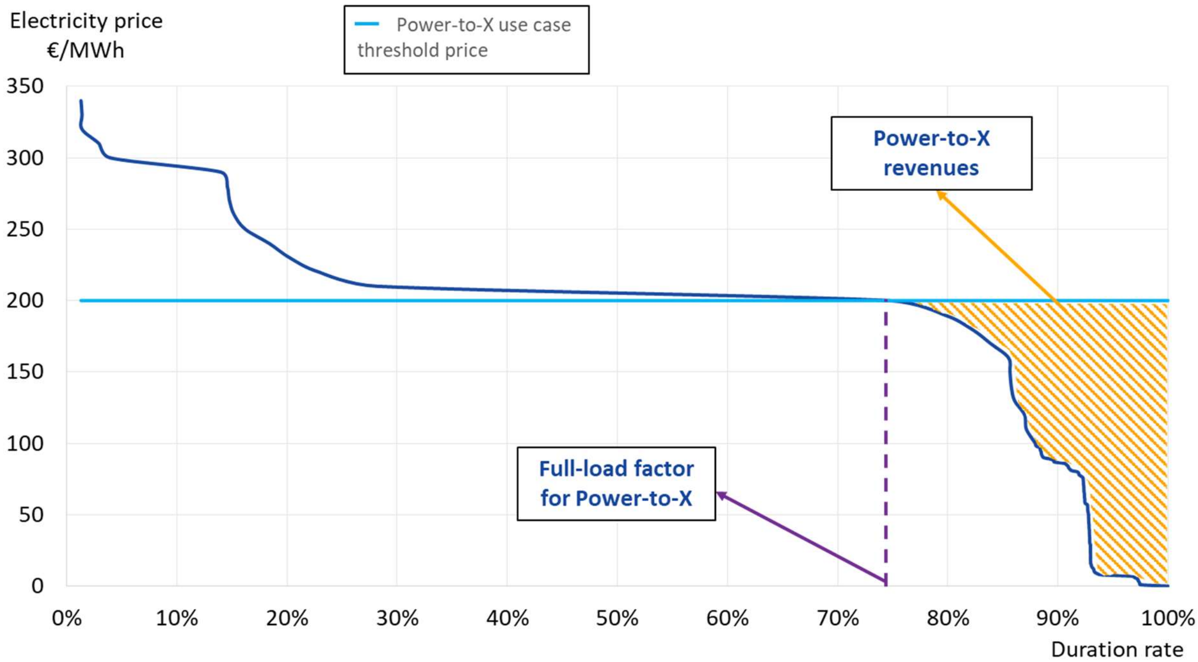
where T is the lifetime and r the discount rate (8.5% according to the EU reference scenario[9])

If the annual revenues exceed the annualised investment costs, the power-to-X technology is profitable. Because the projected economic parameters are subject to a significant uncertainty, a sensitivity analysis on the CAPEX and OPEX is added. Minimum and maximum data from the literature are used to assess the profitability on the range of possible annualised investment costs found the literature. For all other parameters, average values are applied.

[9] Further details on EU reference scenario are available at https://ec.europa.eu/energy/en/data-analysis/energy-modelling

This methodology in summarised and illustrated in the following Figure for an exemplary synthetic use case. In the example, a hypothetic power-to-X technology is competitive when electricity prices are lower than 200 €/MWh$_{el}$. Such prices occur in about 2 200 hours per year in the EUCO30 2050 scenario (cf. 6.3), inducing a full load factor for the power-to-X technology of about 25%. The revenues equal the orange-shaded area, which represent the difference between the electricity price and the threshold price[10] in all hours with prices below 200 €/MWh.

Figure 21 – Power-to-X full-load factor versus the threshold electricity price to use power-to-X. Example with a threshold price of 200 €/MWh.



The three next paragraphs detail the threshold electricity prices computation for three different power-to-X use cases. Then, in Section 7, the revenues are assessed on the studied EUCO30 2050 scenario and compared to the technology investment costs, as explained above.

5.3. USE CASE 1: POWER-TO-H_2 VS SMR + CCS

The use case 1 assesses the competitiveness of power-to-H_2 assuming that there is no H_2 storage capacity available. A flat and inelastic hydrogen demand is assumed, which is typically representative of an industrial demand. The benchmark technology is Steam Methane Reforming combined with CCS (SMR + CCS, see Figure 22).

[10] that is, from the power-to-X unit's standpoint, the difference between the product selling price and the feedstock buying price.

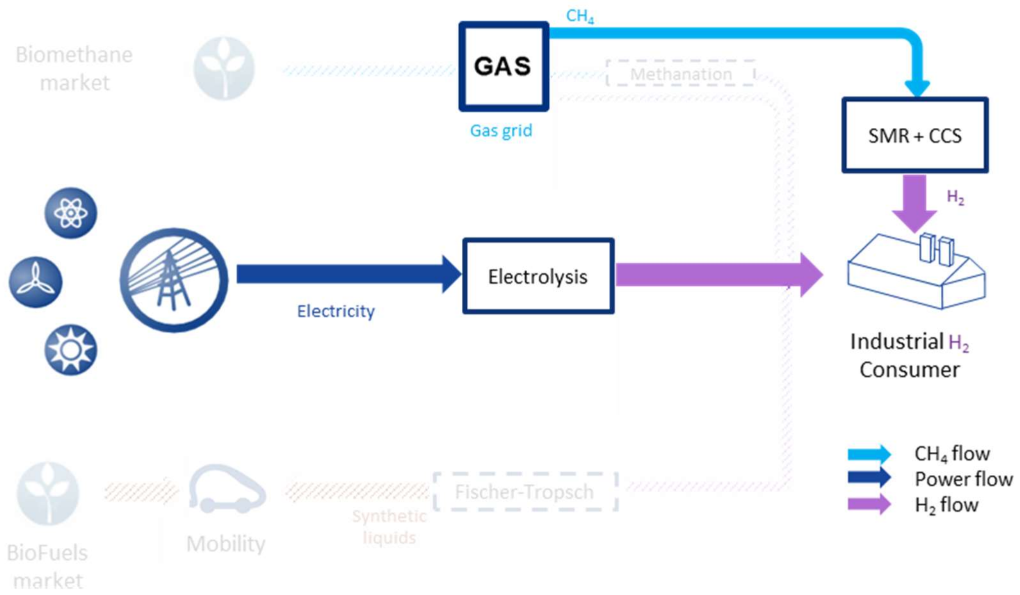


Figure 22 - Schematic overview of use case 1: power-to-H_2 vs SMR + CCS

As synthetic hydrogen can be provided only during hours with sufficiently low electricity prices, the SMR (and the corresponding fixed costs) remain necessary as a back-up. The threshold price is consequently computed taking into account only variable costs:

$$thresholdPrice = productionCost(SMR + CCS) \cdot efficiency(PtoH_2)$$

Table 3 lists all major parameters used in use case 1. Based on these values and the methodology described previously, the **threshold electricity price is 37.4 €/MWh$_{el}$.** The annualised investment costs range between **68.2 and 113.3 €/kW$_{el}$/year.**

Table 3 - Data used for use case 1

Parameters		**Value**	**Unit**
Power-to-H_2	Efficiency	82%	MWh$_{H2\ HHV}$ /MWh$_{el}$
	Lifetime	20	years
	CAPEX	500 - 725	€/kW power
	OPEX	3% - 5%	% of CAPEX
Benchmark technology: SMR + CCS	Production cost	45.81	€/MWh$_{H2\ HHV}$

The variable production costs of SMR +CCS are computed using the natural gas price from the European Commission's EUCO30 scenario for the year 2050 (35.27 €/MWh$_{CH4\ HHV}$) and an SMR + CCS efficiency deduced from literature survey (77%, see 4.2.2). As explained in Section 4.2.2, a 100% CO_2 capture rate is assumed.

Furthermore, a **variant** of this use case has been investigated. A H_2 storage is added to the electrolysis in order to avoid maintaining the SMR + CCS infrastructure as back-up (see Figure 23). Combined with a H_2 storage, the electrolysis facility can indeed supply the H_2 demand all year long by filling the storage during low electricity price periods (the stored H_2 being then used when the electrolysis is not running because electricity prices are too high). In this variant, the electricity threshold price is different as the power-to-H_2 project can also avoid the fixed costs of the SMR.

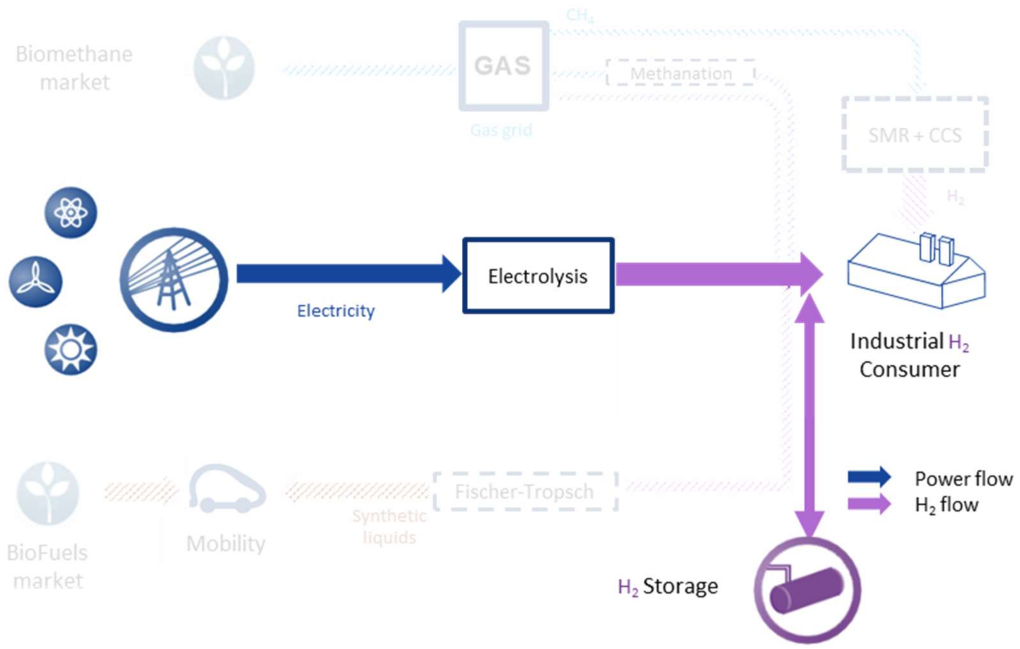


Figure 23 - Schematic overview of variant use case 1: power-to-H_2 + H_2 storage

The difference between this variant and the standard use case 1 (where power-to-$H_2$is considered without storage) can be described in practical terms as follows: in the first case, both technologies have to be present to guarantee a reliable supply. The optimal utilisation of each technology depending on power price is based on variable costs only. If the electrolyser can have access to a large-scale hydrogen storage capacity, the electrolyser can replace completely the SMR. It is then competitive to run the electrolyser only if its variable cost (cost to produce one extra MWh of hydrogen) is lower than the total cost of SMR+CCS : one extra MWh of hydrogen can save corresponding SMR variable costs plus 1/8760 of SMR+CCS annualised CAPEX cost :

$$productionCost(PtoH_2) \leq productionCost(SMR + CCS) + annualisedInvestment(SMR + CCS) \,/\, 8760$$

The threshold electricity price is then defined as:

$$thresholdPrice = (productionCost(SMR + CCS) + annualisedInvestment(SMR + CCS)/8760) \cdot efficiency(PtoH_2)$$

The threshold price for the variant case is higher than for the use case 1 which is coherent because the electrolysis generates more savings. However, the related potential increase in revenues for power-to-H_2 production has to be compared to the total investment costs, including the H_2 storage unit:

$$annualisedInvestment = annualisedCapex(PtH_2) + Opex(PtH_2) + investmentCost(StorageH_2)$$

Data for storage costs is based on [28], assuming the utilisation of pre-existing underground storage (i.e. no mining costs): 0.125 €/kg H_2[11]. Consequently, the threshold electricity price for the variant of use case 1 is **47.1 €/MWh$_{el}$** and annualised investment costs range between **70.5 and 115.6 €/kW$_{el}$/year.**

[11] To compute an annual investment cost from the storage cost, a one-month maximum storage has been assumed: 0.125 €/kg$_{H2}$ = 3.125 €/MWh$_{H2\ HHV}$ which gives 2,3 €/kW$_{H2\ HHV}$.

5.4. USE CASE 2: POWER-TO-CH_4 VS BIOMASS-TO-CH_4

Use case 2 compares power-to-CH_4 with the benchmark technology biomass-to-CH_4. Generated CH_4 is assumed to be injected into the gas grid (which can store it if needed) and compare the economics of power-to-CH_4 to the total cost of biomass-to-CH_4 generation (see Figure 24).

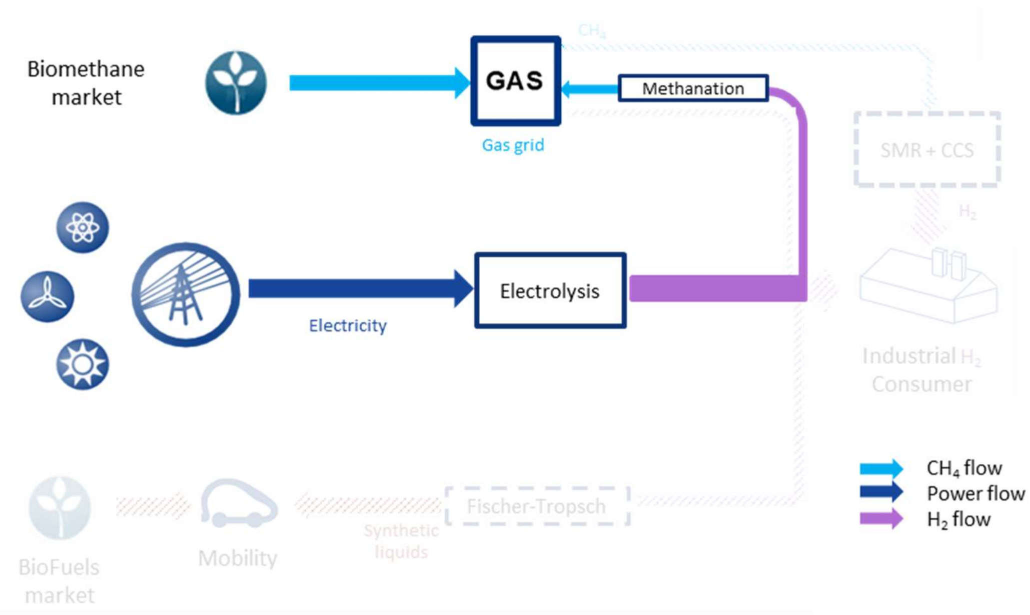


Figure 24 - Schematic overview of use case 2: power-to-CH_4 vs biomass-to-CH_4

The threshold electricity price is constructed as follows:

$$productionCost(PtoCH_4) = \frac{electricityPrice}{efficiency(PtoCH_4)} + methanationCost(CO_2)$$

$$thresholdPrice = (productionCost(BioCH_4) - methanationCost(CO_2)) \cdot efficiency(PtoCH_4)$$

$methanationCost(CO_2)$ is the cost to capture the CO_2 needed for the methanation process.

The literature survey on biomass-to-CH_4 reveals a large uncertainty concerning the 2050 projection of its production cost (see Section 4.3.2). To be coherent with others projection data for this use case, production costs of 90.5 €/MWh$_{CH4\ HHV}$ are assumed. Data used for the use case 2 are listed in Table 4. The resulting **threshold electricity price is 53.3 €/MWh$_{el}$** and the annualised investment costs range between **108.5 to 204.6 €/kW$_{el}$/year** (investment costs for electrolysis and H_2-to-CH_4 (methanation) are included). A sensitivity analysis has been performed on the biomethane production cost: a use case 2* is carried out assuming a biomethane production cost of 106 €/MWh$_{CH4\ HHV}$.

Table 4 - Data used for use case 2

Parameters		Value	Unit
H_2-to-CH_4	Efficiency	79%	MWh$_{CH4\ HHV}$ / MWh$_{H2\ HHV}$
	Lifetime	25	years
	CAPEX	500 - 700	€/kW$_{CH4}$
	OPEX	3% - 10%	% of CAPEX
CO_2 capture for H_2-to-CH_4	Need of CO_2	0.198	tCO_2/MWh$_{CH4\ HHV}$
	CO_2 cost	40	€/tCO_2

Benchmark technology: biomass-to-CH_4	Production cost	90.50 (106 for variant)	€/MWh$_{CH4\ HHV}$

5.5. USE CASE 3: POWER-TO-LIQUIDS VS BIOMASS-TO-LIQUIDS

Use case 3 focuses on the power-to-Liquids process via the Fischer-Tropsch route in comparison with the biomass-to-Liquids process. Similar to the previous use case, generated synthetic fuel can be stored easily, so we compare the economics of power-to-liquid projects to the total cost of its benchmark biomass-to liquids (cf. Figure 25)

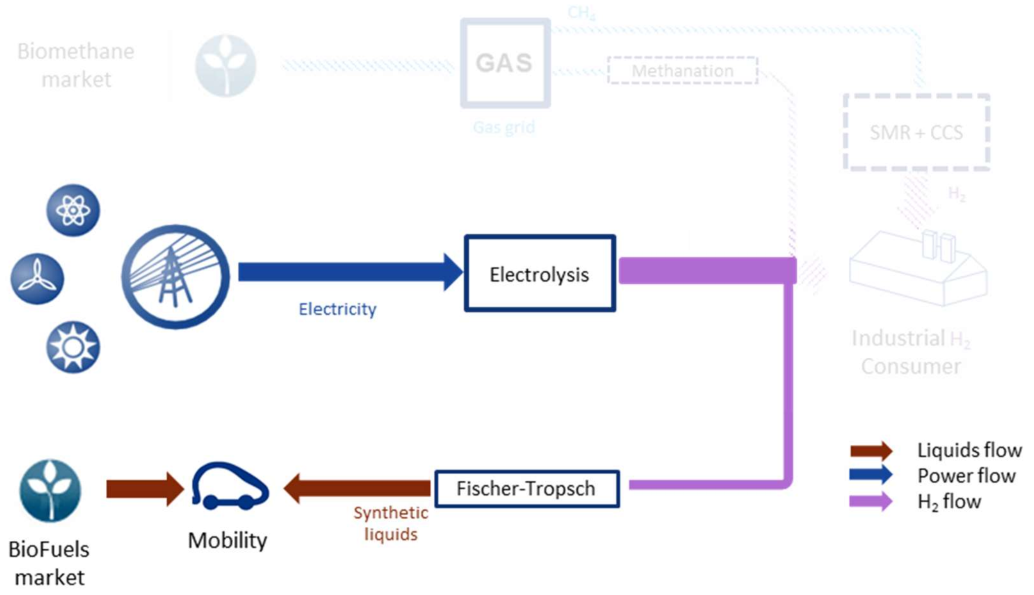


Figure 25 - Schematic overview of use case 3: power-to-Liquids vs biomass-to-Liquids

The threshold electricity price is calculated as follows:

$$productionCost(PtLiquids) = \frac{electricityPrice}{efficiency(PtoLiquids)} + FischerTropschCost(CO_2)$$

$$thresholdPrice = (productionCost(BioFuels) - FischerTropschCost(CO_2)) \cdot efficiency(PtoCH_4)$$

$FischerTropschCost(CO_2)$ is the supply cost of CO_2 needed for the Fischer-Tropsch process. Based on the parameters listed in Table 5, the threshold electricity price is **42.5 €/MWh$_{el}$** with the annualised investment costs ranging between **97.2 to 176.8 €/kW$_{el}$/year** (investment costs of electrolysis and H_2-to-Liquids (Fischer-Tropsch synthesis) are included).

Table 5 - Data used for use case 3

Parameters		**Value**	**Unit**
H_2-to-Liquids	Efficiency	80%	MWh$_{PtL\ HHV}$ / MWh$_{H2\ HHV}$
	Lifetime	30	years
	Capex	365 - 673	€/kW$_{PtL}$
	Opex	3% - 5%	% of CAPEX
CO_2 capture for H_2-to-Liquids	Need of CO_2	0.251	tCO_2/MWh$_{PtL\ HHV}$
	CO_2 cost	40	€/tCO_2
Benchmark technology: biomass-to-Liquids	Production cost	75,00	€/MWh$_{PtL\ HHV}$

6. SCENARIO DEFINITION AND ANALYSIS

This section reveals to what extend the threshold electricity prices identified for the different use cases could be reached in a given 2050 scenario. For this purpose, this section shortly summarises the METIS power system model which is used to determine hourly national marginal generation costs for all countries of the EU for a 2050 scenario (Section 6.1). Secondly, this scenario, the European Commission's EUCO30-2050 scenario, is introduced (cf. Section 6.2). Ultimately, a focus on electricity prices by 2050 is depicted (cf. Section 6.3).

6.1. METIS POWER SYSTEM MODEL

METIS is an on-going project[12] initiated by the European Commission's DG Energy for the development of an energy modelling software, with the aim to further support DG Energy's evidence-based policy making, especially in the areas of electricity and gas. The model is developed by a consortium (Artelys, IAEW, ConGas, Frontier Economics), which already delivered a version of METIS covering the power and gas system and market modules.[13]

METIS is an energy modelling software covering in high granularity (in time and technological detail, as well as representing each Member State of the EU and relevant neighbouring countries) the whole European power system and markets. METIS relies on the Artelys Crystal Super Grid platform. This platform provides a graphical user interface, optimisation services and scripting capabilities that allow the user to extend the software according to his individual needs.

METIS includes its own modelling assumptions, datasets and comes with a set of pre-configured scenarios. These scenarios usually rely on the inputs and results from the European Commission's projections of the energy system, for instance with respect to the capacity mix or annual demand. Based on this information, METIS allows to perform the hourly dispatch simulation (for the length of an entire year, i.e. 8760 consecutive time-steps per year). The result consists of the hourly utilisation of all national generation, storage and cross-border capacities as well as demand side response facilities.

The uncertainties regarding the demand and renewable power generation dynamics are captured thanks to a set of 50 weather scenarios taking the form of hourly time-series of wind, irradiance and temperature, which influence demand (through a thermal gradient), as well as PV and wind generation.

6.2. THE EUCO30 2050 SCENARIO

The European Commission's EUCO30 scenario has been developed to reach all the 2030 targets agreed by the October 2014 European Council (at least 40% reduction in greenhouse gas emissions with respect to 1990, 27% share of RES in final energy consumption and 30% reduction in the primary energy consumption) and the 2050 decarbonisation objectives (80-95% greenhouse gas emission reduction compared to 1990), continuing and intensifying the current policy mix. In the EUCO30-2050 scenario, it is supposed that by 2050 renewables represent 65% in the EU's net electricity generation and variable renewables like solar and wind power make up for close to 50% of the overall production. Final electricity demand is expected to reach 3 250 TWh_{el} at the EU level[14]. The EUCO30-2050 scenario assumes a high CO_2 price signal of more than 100 €/t_{co2} for the EU ETS.

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[12] See http://ec.europa.eu/dgs/energy/tenders/doc/2014/2014s_152_272370_specifications.pdf

[13] For further information see https://ec.europa.eu/energy/en/data-analysis/energy-modelling/metis

[14] For further details see https://ec.europa.eu/clima/sites/clima/files/effort/docs/technical_report_euco_scenarios_primes_en.pdf

6.3. ELECTRICITY PRICES IN EUCO30 2050 SCENARIO

The hourly electricity price time series determined with the METIS simulations for the EUCO30-2050 scenario differ substantially between EU Member States. The price duration curves exhibit three major price levels:

- A low-price level (<10 €/MWh) set by RES and nuclear production (~7-8 €/MWh).
- Intermediary-price levels (90 €/MWh and 190-210 €/MWh) corresponding respectively to biomass power plants and CCGT (Combined Cycle Gas Turbine) marginality.
- A high-price level with prices close to or above 300 €/MWh set by other thermal power plants: OCGT (Open Cycle Gas Turbine) (~300 €/MWh), lignite power plant (420 €/MWh) and coal power plant (440€/MWh).

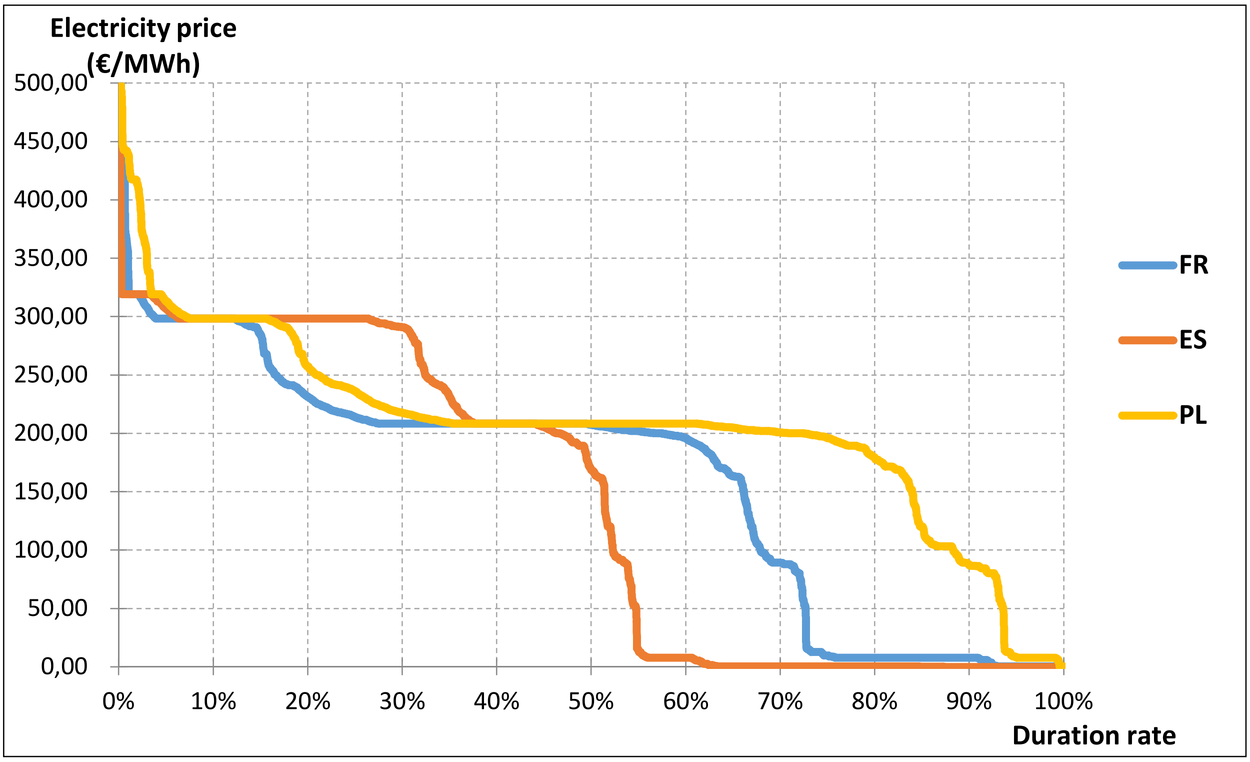

Figure 26 - Price duration curves for three selected countries

Figure 26 provides three typical electricity price patterns. In power mixes like Spain's, with a lot of baseload generation completed by peakers, prices vary from low levels (< 10 €/MWh) straight to high levels (> 300€/MWh) with few occurrences of intermediate price levels (less than 10% of the year). In the case of Spain, the baseload generation includes high shares of uncontrollable RES (cf. Table 6), with PV solar and wind power accounting for over 65% of the national generation. As shown on Figure 27, such a power mix leads to alternating rapidly between overbalance (typically around midday when PV generation is at its peak and power is very cheap) and supply scarcity (typically at night when imports and peakers are required to replace PV generation). In this context, the economic value of flexibility solutions can be very high, as short-term flexibility requirements are significant. Member States like Portugal or Cyprus, featuring high RES shares, exhibit the same type of price duration curves.

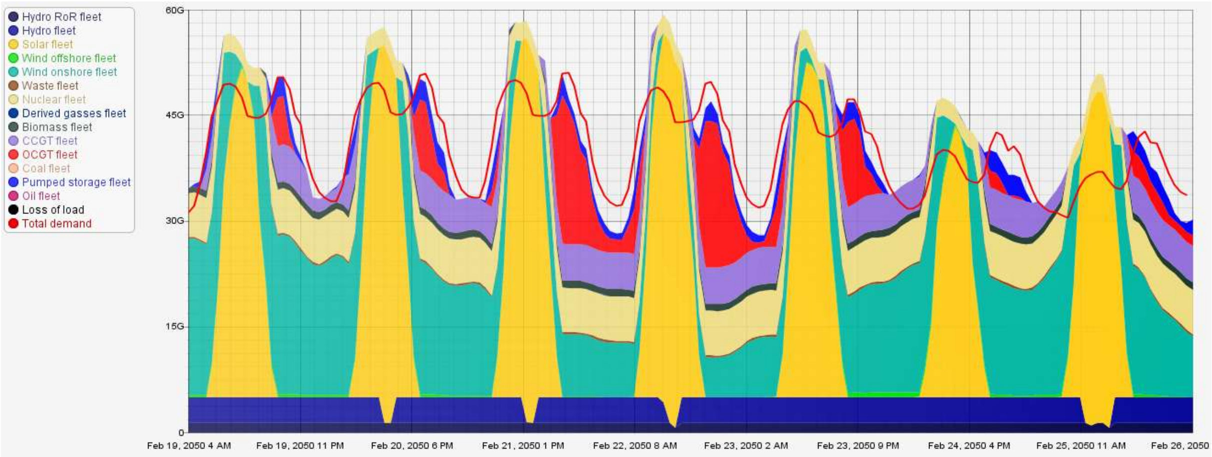

Figure 27 : Cumulative generation types in Spain for a week in early February (METIS EUCO30 2050)

In contrast, the power mix of Poland is such that baseload generation is hardly ever enough to meet the demand. It can be completed by imports from neighbours like Germany with high RES shares and frequent power surplus. However, despite being a significant flexibility provider, interconnections have to be backed-up by gas-to-power to balance supply and demand. As a consequence, electricity prices are found to be quite stable at high values: they correspond to CCGTs variable costs during 40% of the year and higher or equal than CCGTs variable costs during 80% of the year. Countries like Romania, Slovenia and Netherlands (among others) have a similarly-shaped price duration curve.

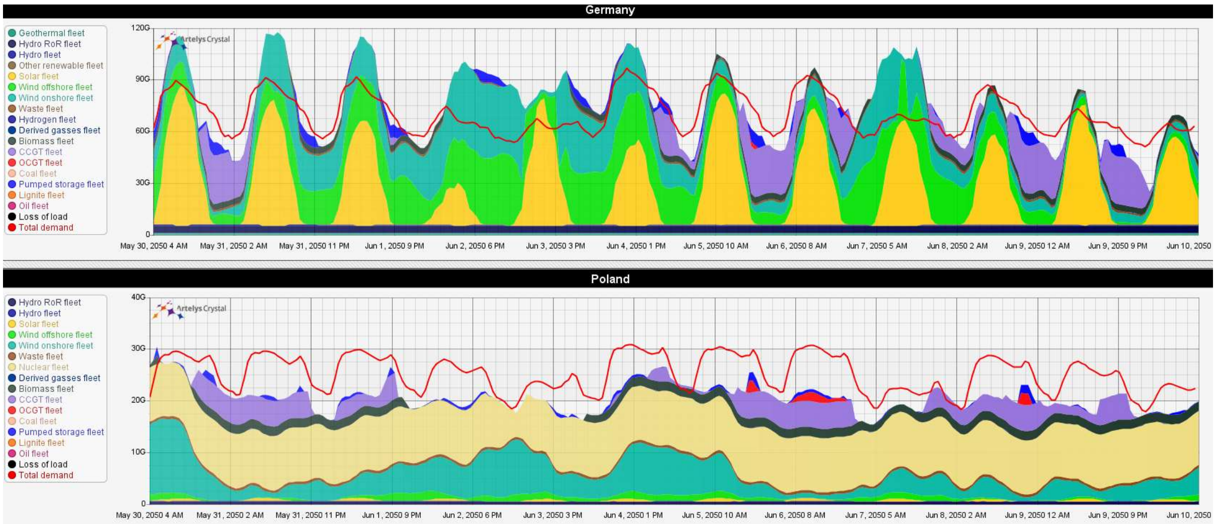

Figure 28:Cumulative generation types in Germany and Poland (May, 30th to June, 10th)

Between these two price duration curves, a lot of countries exhibit intermediate patterns, like France with a more heterogeneous power mix.

The contrast of electricity price between countries is also illustrated on Figure 29. This figure provides the duration of electricity prices lower than 5 and 10 €/MWh for every European country.

Figure a) confirms that electricity prices can be frequently low (only) in countries with high RES penetration like Spain, Portugal, Greece, Ireland or Cyprus. Such countries have a RES production share in their respective national productions ranging from 54% to 74%. Figure b) includes periods where nuclear power plants are marginal and set the electricity prices.

7. PROFITABILITY OF POWER-TO-X IN 2050

7.1. COMPETITIVENESS OF POWER-TO-X IN 2050

Table 6 provides the potential utilisation rate of power-to-X technologies (i.e. percentage of time when electricity prices are lower than the threshold prices of each power-to-X technology, as explained in §5.2). As one may expect, countries with the highest utilisation rates are Cyprus, Spain, France, Greece, Ireland and Portugal, which are the countries with the longest low electricity price periods (see previous section for a more detailed analysis of electricity prices in the considered scenario).

a) Power marginal cost < 5 €/MWh *b) Power marginal cost < 10 €/MWh*

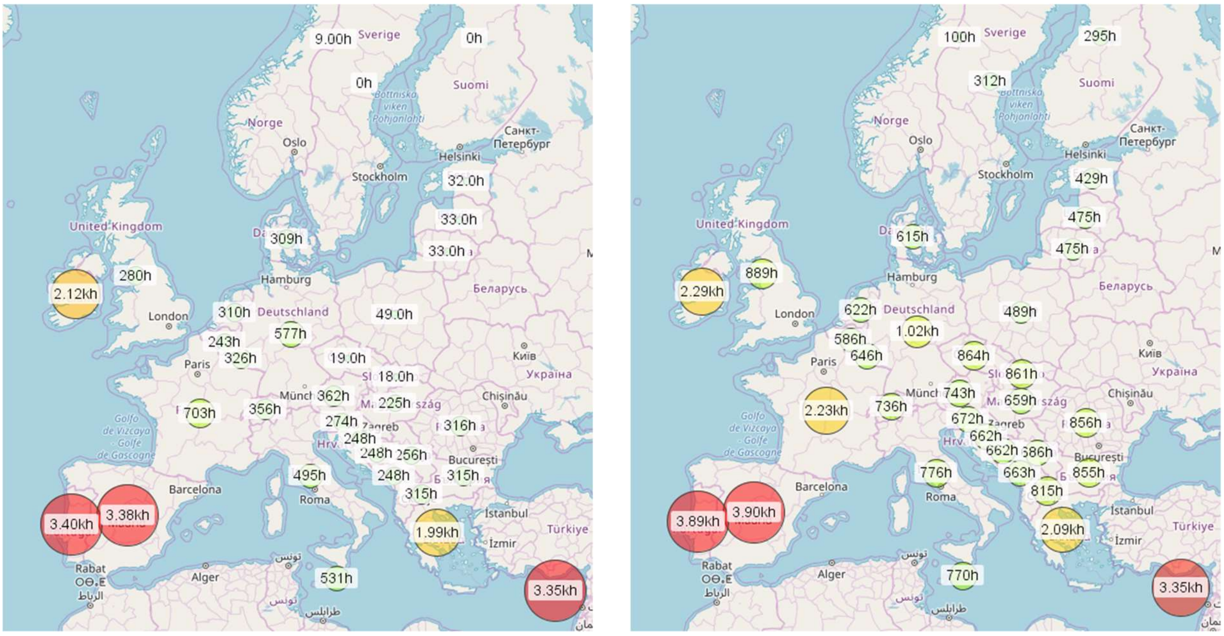

Figure 29 – Duration of electricity price lower than a selected threshold price

Table 6 - Duration of electricity prices lower than the threshold prices of power-to-X. For each country, the average price of electricity and the RES penetration are also provided

	Potential utilisation rate of power-to-X technologies			**Electricity price characteristic**	**RES penetration**
	Use case 1 threshold price: 37.4 €/MWh$_{el}$	Use case 2 threshold price: 53.36 €/MWh$_{el}$	Use case 3 threshold price: 42.50 €/MWh$_{el}$	Average price (€/MWh$_{el}$)	RES share in national production (%)
AT	8.9%	9.1%	8.9%	200	37%
BA	7.8%	7.9%	7.9%	216	14%
BE	7.1%	7.3%	7.2%	202	50%
BG	10.1%	10.3%	10.2%	211	43%
CH	8.9%	9.0%	8.9%	200	5%
CY	38.2%	38.2%	38.2%	161	61%
CZ	10.5%	10.7%	10.5%	195	12%
DE	12.3%	12.5%	12.3%	193	67%
DK	7.6%	7.9%	7.6%	181	71%
EE	5.5%	6.0%	5.6%	187	64%
ES	45.2%	45.6%	45.2%	145	66%
FI	3.8%	4.5%	3.9%	173	11%
FR	27.3%	27.5%	27.3%	164	42%
GB	11.1%	11.3%	11.1%	191	40%
GR	24.2%	24.2%	24.2%	188	74%
HR	7.8%	7.9%	7.9%	215	39%
HU	7.8%	7.9%	7.8%	214	17%
IE	26.5%	26.7%	26.5%	165	69%
IT	9.1%	9.2%	9.1%	212	47%
LT	6.1%	6.6%	6.2%	186	30%
LU	7.7%	8.1%	7.8%	202	36%
LV	6.1%	6.6%	6.2%	186	51%
ME	7.8%	8.0%	7.9%	216	26%
MK	9.6%	9.8%	9.7%	216	7%
MT	9.0%	9.1%	9.0%	189	35%
NL	7.6%	7.8%	7.7%	201	51%
NO	1.3%	1.7%	1.3%	179	8%
PL	6.3%	6.5%	6.4%	206	31%
PT	45.0%	45.4%	45.1%	145	54%
RO	10.1%	10.3%	10.2%	211	45%
RS	8.1%	8.3%	8.2%	215	9%
SE	4.1%	4.7%	4.2%	171	19%
SI	7.9%	8.0%	8.0%	214	23%
SK	10.4%	10.7%	10.5%	196	3%

With threshold prices ranging from 37 to 53 €/MWh, the three use cases yield similar power-to-X full load hours in most Member States. Indeed, as shown in section 6, electricity prices are mainly lower than 10 €/MWh (RES or nuclear marginality) or greater than 200 €/MWh (fossil-fuel based generation being marginal). Consequently, the different power-to-X technologies are found to have similar competitiveness against their respective benchmark technologies in terms of variable costs.

However, the potential utilisation rate of power-to-X technologies does not indicate whether the technology is profitable or not, but merely shows for how many hours per year the power-to-X technology is more competitive than the benchmark technology (in terms of variable costs). In order to evaluate the profitability of the power-to-X technologies, it is necessary to determine the revenues associated to each power-to-X technology and to contrast them with their individual fixed costs.

7.2. USE CASE 1: POWER-TO-H_2 VS SMR + CCS

A given power-to-X technology is profitable if the average annual market revenues exceed the fixed costs CAPEX plus OPEX[15]. This section provides assessment of the profitability of the three different technologies considered.

Figure 30 shows the average annual revenues for power-to-H_2 (blue crosses) and the range of fixed costs[16] projections for 2050 found in the literature[17] (area between the dotted orange lines). Figure 30 As expected, power-to-H_2 has a large potential for countries where electricity prices remain at low levels for a significant overall duration during the year.

Under the assumptions used:

- power-to-H_2 would be profitable in Cyprus, Spain and Portugal even for the highest fixed costs considered. In those countries the electricity prices are lower than the threshold electricity price (37 €/MWh) during 38% to 45% of the year.
- In France, Greece and Ireland, on the other hand - with electricity prices being under 37€/MWh for approximately 25% of the year - it would only be profitable if fixed costs in 2050 are in line with the most optimistic projections available at the time of writing this report.
- For other countries, low electricity prices would not occur during a long enough cumulated duration to cover the investment costs. In such cases, H_2 would be supplied by SMR combined with CCS.

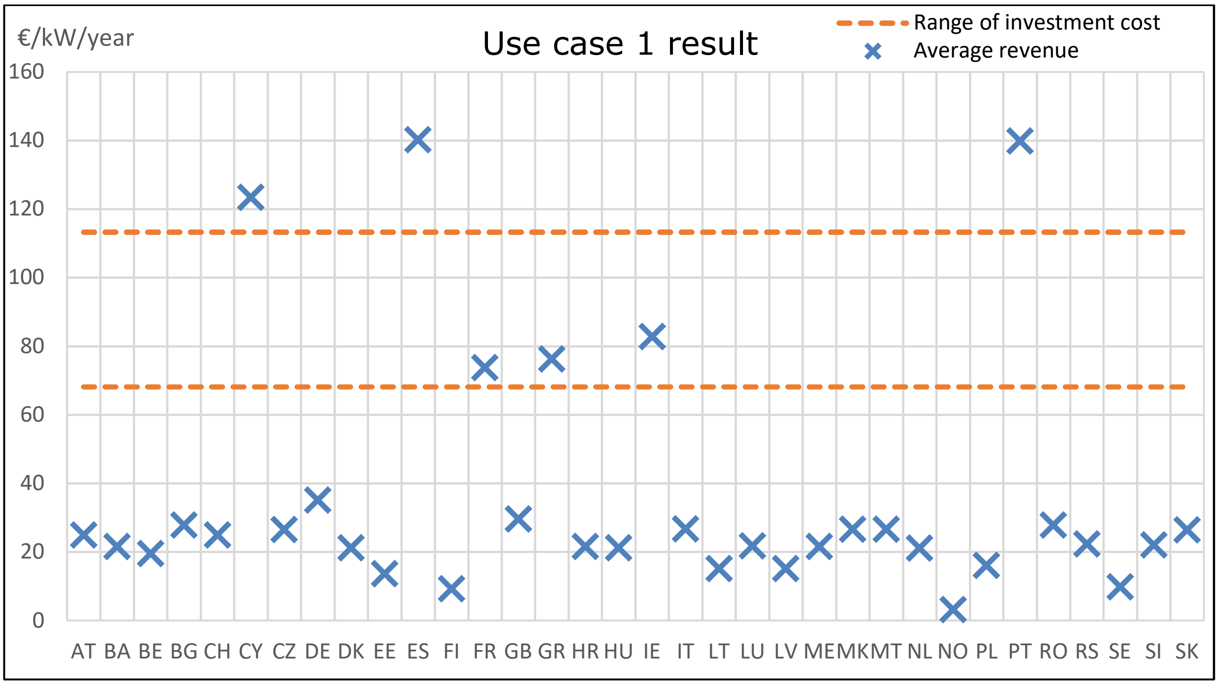

Figure 30 - Average annual revenue compared to the annual investment cost for power-to-H_2 in the case of competition with SMR + CCS

As mentioned in section 5.3, assuming that a large H_2 storage is combined with the electrolysis, the corresponding threshold electricity price making this installation competitive would increase to 47 €/MWh. However, investment costs are also higher since

[15] See the methodology described in Section 5.2 for details.

[16] Fixed costs are annualised in order to be comparable with annual revenues.

[17] All technical or economic data used here comes from the literature review presented in details in Section 4.

they include the storage facility investment cost. Figure 31 shows the profitability assessment corresponding to this variant. One can observe that, even though the profitability increase for countries with high RES or nuclear shares, the impact is limited. It is nonetheless worth noticing that the profitability projections appear to be more robust for intermediate countries - France, Greece and Ireland – as a broader range of the investment costs projections can be covered. Besides, since profitability of the first MW is higher, one may expect the economic deployment potential to be greater as well. This was not assessed in this study but is part of METIS study S1.

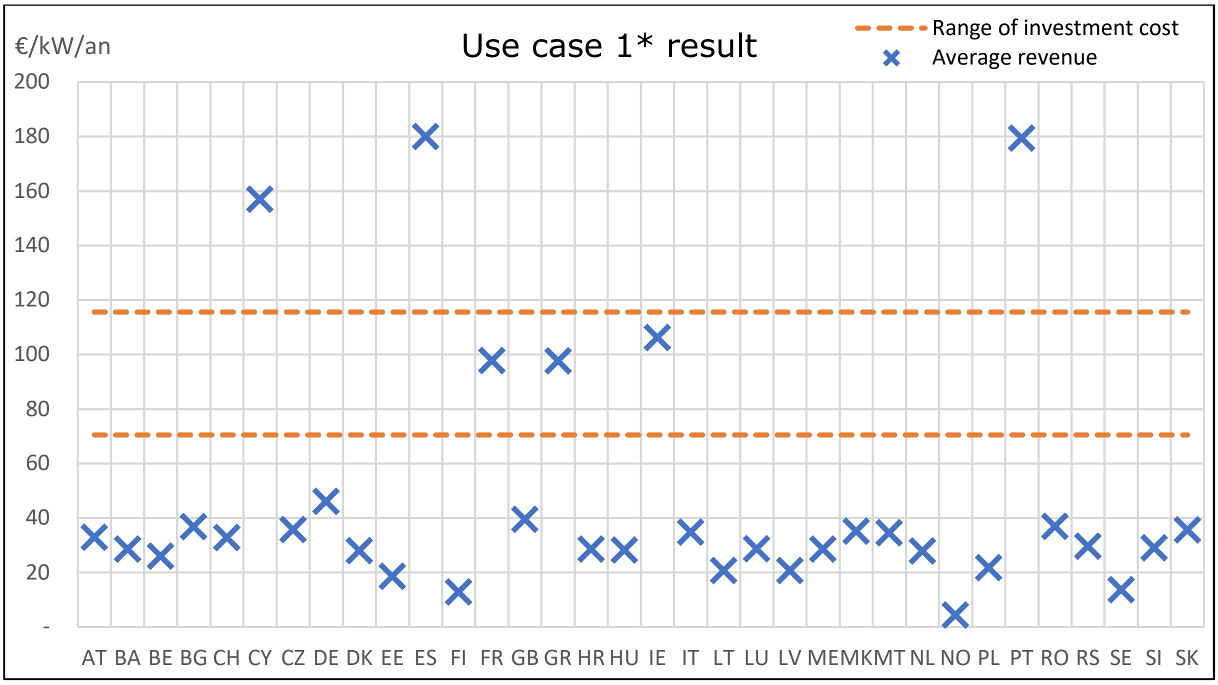

Figure 31 - Average annual revenue compared to the annual investment cost for power-to-H_2 with H_2 storage in the case of competition with SMR + CCS

7.3. USE CASE 2: POWER-TO-CH_4 VS BIOMASS-TO-CH_4

Figure 32 shows the profitability of power-to-CH_4 in competition with biomass-to-CH_4 (biomethane). Similar to use case 1, power-to-CH_4 could be profitable by 2050 in countries with very low electricity prices, namely Cyprus, Spain, France, Greece, Ireland and Portugal. However, in all of these countries, the profitability depends on the assumptions on CAPEX projection for 2050. For all other countries, power-to-CH_4 does not exhibit a commercial advantage under the assumption used for electricity prices and techno-economic characteristic of power-to-CH_4 technologies. In this context, decarbonised CH_4 production would probably be generated through biomass-to-CH_4.

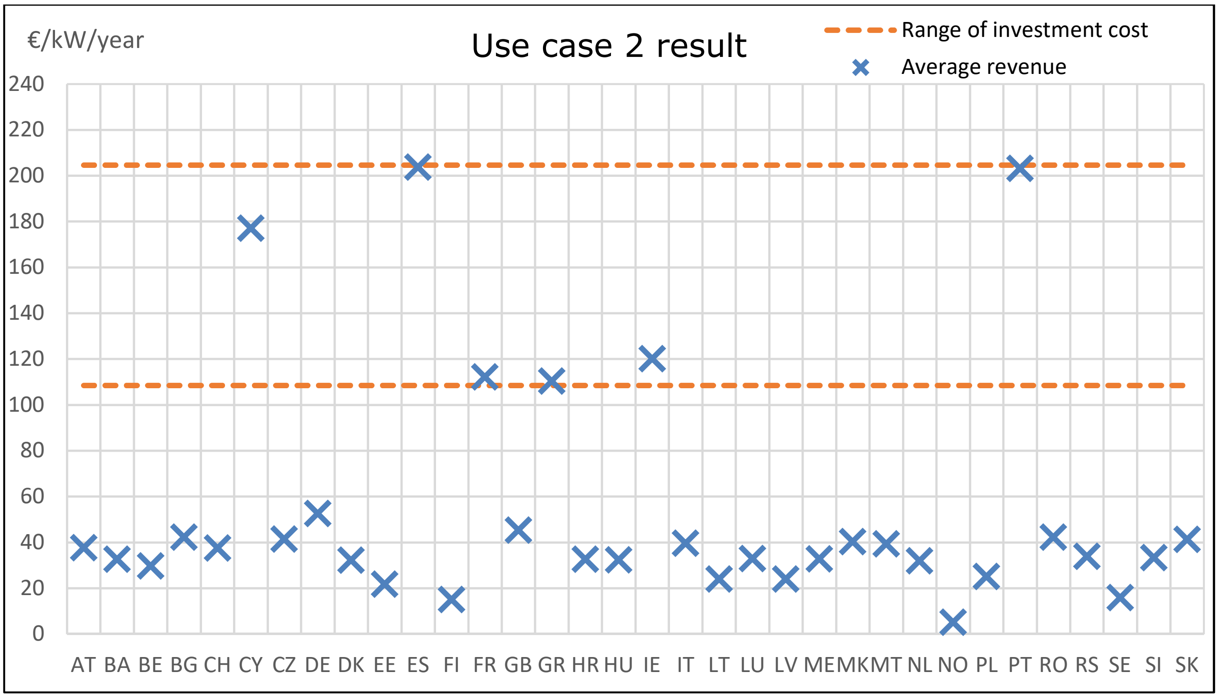

Figure 32 - Average annual revenue compared to the annual investment cost for power-to-CH_4 in the case of competition with biomass-to-CH_4 (production cost of biomethane = 90.5 €/MWh$_{CH4\ HHV}$)

Power-to-CH_4 could be profitable compared to the average CAPEX data for countries having approximately 3000 hours of very low electricity prices (4000 hours in the comparison case with the upper end of CAPEX data). According to Figure 29, EUCO30 2050 scenario sets up this configuration only in Cyprus, Portugal and Spain.

Compared to power-to-H_2, power-to-CH_4 induces more investment costs and a decreased efficiency[18] at the same time. Consequently, CH_4 has to be significantly more valuable than H_2 to make methanation economically relevant, which depends on the availability of other sources of carbon-free CH_4. To illustrate the sensitivity of $H_2 - \text{to} - CH_4$ economic value to the market price of carbon-neutral CH_4, a variant was considered with higher production costs for biomethane (106 instead of 90.5 €/MWh$_{CH4\ HHV}$). As one can see on Figure 33, in this sensitivity the profitability patterns appear to be more aligned on that of power-to-H_2, which shows that the interest of methanation highly depends on the availability and cost of alternative solutions to decarbonise CH_4

- In countries with very high RES shares like Spain, Cyprus or Portugal, the first MW of power-to-CH_4 may be profitable in 2050 even for pessimistic CAPEX projections.

- For countries with considerable baseload (but fewer RES surplus than Spain, Cyprus and Portugal) - like France, Ireland and Greece - power-to-CH_4 may be profitable in 2050 provided that investment costs correspond to the current optimistic projections.

- For other countries, electricity prices would be too high to cover power-to-CH_4 investment costs.

[18] Only low temperature electrolysis has been considered in this study. With high-temperature electrolysis, part of the heat generated by the methanation could be used for the water electrolysis needed to supply the H_2 required for methanation. As a consequence, the whole chain efficiency decrease (due to the methanation part) could be much more limited.

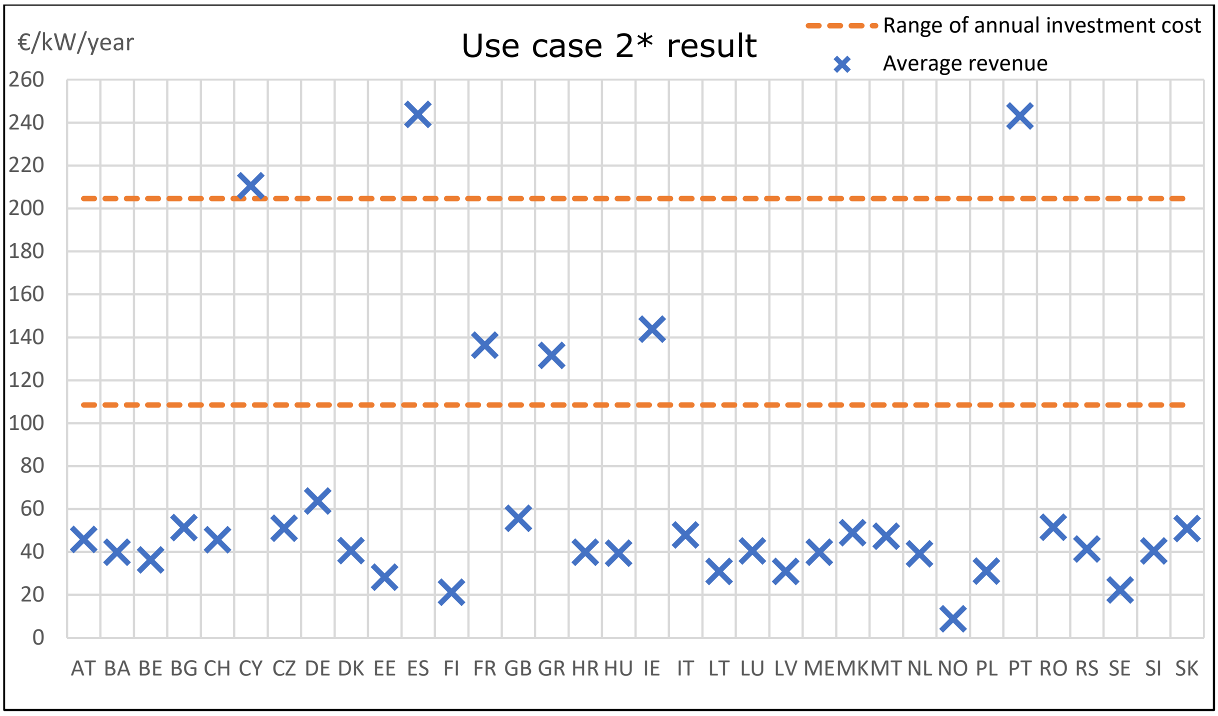

Figure 33 - Average annual revenue compared to the annual investment cost for power-to-CH_4 in the case of competition with biomass-to-CH_4 (production cost of biomethane = 106 €/MWh$_{CH4\ HHV}$)

7.4. USE CASE 3: POWER-TO-LIQUIDS VS BIOMASS-TO-LIQUIDS

Figure 34 reveals the profitability of the power-to-Liquids technology in comparison with advanced biofuels under the assumption of 75 €/MWh$_{PtL\ HHV}$ as production cost for biofuels. Power-to-Liquids technology is found to be less profitable than power-to-H_2 and power-to-CH_4. Merely in Cyprus, Spain and Portugal, revenues would cover the most optimistic CAPEX projections for 2050. However, as many technologies are not mature yet, little data is available on the projected techno-economic characteristics for carbon-free liquids in 2050. The results of use case 3 should therefore be interpreted with reserve.

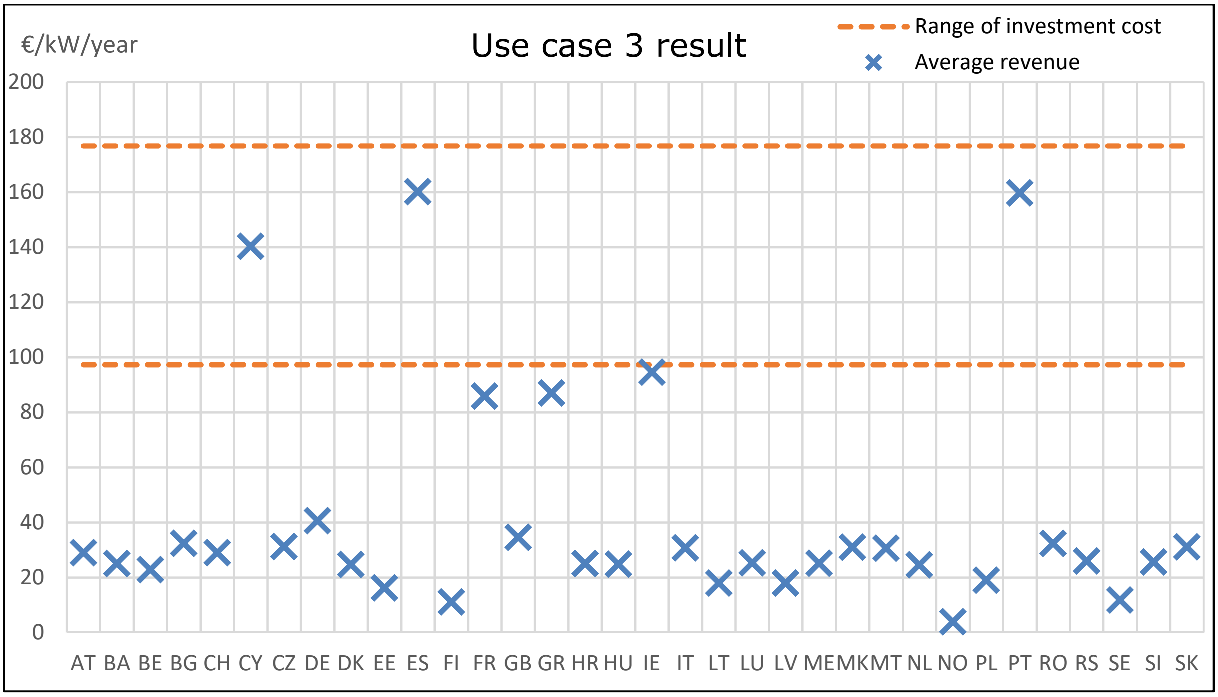

Figure 34 - Average annual compared to the annual investment cost for power-to-Liquids in the case of competition with biomass-to-Liquids (production cost of biofuel = 75 €/MWh$_{PtL\ HHV}$)

Like power-to-CH_4, power-to-Liquids could be profitable compared to the average or to the upper-end of CAPEX data for countries having roughly 3000 hours or 4000 hours of very low electricity prices respectively. According to Figure 29, only Cyprus, Portugal and Spain have this low electricity price duration.

8. CONCLUSION AND OUTLOOK

This study analyses the competitiveness of the spontaneous introduction of 1 MW of power-to-X technologies in the year 2050. It compares three main power-to-X technologies (power-to-H_2, power-to-CH_4 and power-to-liquids) with alternative solutions to decarbonise hydrogen, methane and liquid fuel production, under the European Commission's EUCO30-2050 scenario.

The EUCO30-2050 scenario assumes a high RES share in power production (65% of the EU's net electricity generation) and a very high CO_2 price (>100 €/t_{CO2}). The resulting electricity wholesale market prices follow two major price levels:

- A level of very low prices (<10 €/MWh_{el}) when RES and nuclear plants (featuring close to zero marginal electricity generation costs) set the electricity price
- A level of high prices (>200 €/MWh_{el}) set by thermal power plants that are affected by the high CO_2 price.

Contrasting the hourly wholesale prices with the threshold prices which define the competitiveness of the power-to-X technologies (in comparison with the alternative technology solution) reveals the potential number of full-load hours and revenues of each power-to-X technology, distinguished by the individual EU Member States.

The analysis underlines that the profitability of power-to-X technologies is primarily subject to the availability of low electricity prices, and consequently depends on the national power generation mix. In the studied EUCO30-2050 scenario, frequent low-price periods occur only in Spain, Portugal and Cyprus and, to a lesser extent, in France, Greece and Ireland. However, in these countries, power-to-X technologies will have to compete with other flexibility solutions (storage, interconnection, demand response) which would also benefit from the low power prices. On the other hand, in countries exhibiting high power prices most of the year, additional RES investments would be profitable and would in turn directly diminish power prices. A holistic analysis of these competitions and synergies between power-to-X technologies, alternative flexibility solutions and RES deployment is realised in METIS study S1.

This study further describes the overall potential for the penetration of power-to-X technologies, by analysing different demand scenarios for hydrogen, methane and liquid fuels across the different sectors. However, the analysis of competitiveness considers only a marginal development of power-to-X capacities. With limited availability of alternative solutions to decarbonise gas and liquid fuels, significant capacities of power-to-X may be required in 2050. The related additional power demand will impact power prices and will require to install additional capacities of low-carbon power generation units. The corresponding impact on the power system is likewise studied in METIS study S1.

Finally, the downstream chain of gas and liquid fuels is not modelled in this study. A number of factors – such as the distance between hydrogen consumers and large-scale storage or the required level of hydrogen pressure – would have a significant impact on the full implementation cost of power-to-X solutions. More generally, a direct electrification of gas/liquid end-uses may be considered instead of decarbonizing gas/liquid in the first place. Such considerations require further and specific assessments.

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