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FACULTY OF ELECTRICAL ENGINEERING

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UNIVERSITY „GOCE DELCHEV" - SHTIP
FACULTY OF ELECTRICAL ENGINEERING

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PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA.***

ETIMA has a goal to gather the scientists, professors, experts and professionals from the field of technical sciences in one place as a forum for exchange of ideas, to strengthen the multidisciplinary research and cooperation and to promote the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.

Conference ETIMA was held as online conference where contributed more than sixty colleagues, from six different countries with forty papers.

We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA'21 by presenting the results of their current research activities and by launching the new ideas through many fruitful discussions.

We invite you and your colleagues also to attend ETIMA Conference in the future. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information in direct contact, as well as to enjoy the social events together.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот Гоце Делчев.

ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да претставува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живеењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.

Конференцијата ЕТИМА се одржа online и на неа дадоа свој допринос повеќе од шеесет автори од шест различни земји со четириесет труда.

Сакаме да ја искажеме нашата благодарност до сите колеги кои допринесоа за успехот на ЕТИМА'21 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Ве покануваме Вие и Вашите колеги да земете учество на ЕТИМА и во иднина. Веруваме дека следниот пат ќе имаме можност да се сретнеме, да размениме идеи, знаење и корисни информации во директен контакт, но исто така да уживаме заедно и во друштвените настани.

Организационен одбор на конференцијата

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POWER-TO-X TECHNOLOGIES

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Abstract

The transport, buildings and industry sectors, which still rely on gas and liquid fossil fuels, are the sectors with the highest carbon reduction costs. In this context, Power-to-X technologies, together with the development of low carbon electricity generation facilities look promising for full decarbonization by 2050. This paper describes three types of Power-to-X technologies, the basic principle of Power-to-X systems and the reactions that occur. Then the technical and economic parameters for Power-to-H_2, Power-to-CH_4 and Power-to-Liquids are reviewed, followed by their advantages and disadvantages. An assessment is made of the conditions under which these technologies can compete with the alternative low-carbon production processes by 2050.

Key words: *Power-to-X technologies, Power-to-H_2, Power-to-CH_4, Power-to-Liquids.*

Introduction

All state-signatories to the 2015 Paris Agreement have pledged to reduce greenhouse gas emissions to zero by 2050. To achieve this goal, it is necessary to completely eliminate fossil fuels that pollute the environment. Renewable sources, such as the sun, water, wind, etc., have long been used to produce clean green energy. The production of electricity from renewable sources does not pollute the environment, but still most of the electricity in the world is produced from fossil fuels. However, if 100% of electricity is obtained from renewable energy sources, the problem of environmental pollution from fossil fuels is far from solved. Transport and aviation, as well as certain processes in the chemical industry, still depend on fossil fuels. Because of this, Power-to-X technology has emerged and it makes renewable energies compatible and applicable for these sectors and processes.

Power-to-X (PtX) is a new technology for the production of synthetic fuels and raw materials from electrical energy. X stands for methane, liquid fuels, or solid synthetic fuels.

1. Literature review

As mentioned earlier, this paper describes three types of P2X technologies. Section 2 describes the basic principle of P2X technologies. Then, sections 3, 4 and 5 describe the Power-to-H_2, Power-to-CH_4 and Power-to-Liquids technologies along with the reactions that occur, their advantages and disadvantages and their benchmark technologies, respectively. Finally, in section 6 is given a brief overview of the fields of application for Power-to-X.

2. Basic principle of Power-to-X technologies

The first step in Power-to-X technology is water electrolysis: using electricity as an input process, water decomposes to hydrogen and oxygen atoms. First, hydrogen is produced from water. This process requires electricity produced from renewable sources. Carbon dioxide is then used to convert hydrogen to gas or liquid to serve as fuel. There are several ways to get the carbon dioxide needed in this process: direct air capture, capture from biomass and capture from industry. However, the best way is to capture carbon dioxide directly from the atmosphere, which will reduce its emissions into the air, but this method is also the most expensive.

Water electrolysis:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{2.1}$$

Each P2X conversion path is characterized by a specific combination of technologies that depends on the required inputs and outputs (Figure 1). Electrolyzers are a core component of all P2X systems. There are three main types of electrolyzers:

- Alkaline electrolyzers;
- Polymer electrolyte membrane (PEM) electrolyzers and
- Electrolyzers made of solid oxide electrolysis cells (SOEC).

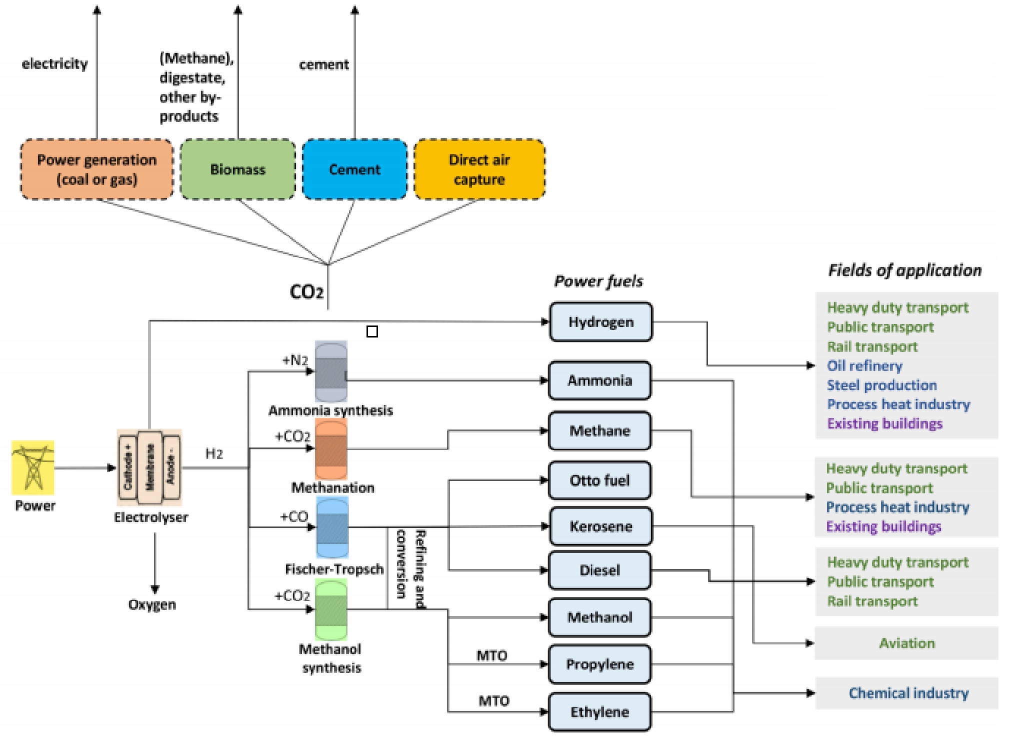

Fig. 1 System diagram of different chains for P2X production with technological alternatives
Source: Perspectives of Power-to-X technologies in Switzerland: A white paper

While alkaline electrolysis is the current water electrolysis technology and is widely used for large industrial applications, PEM electrolyzers are typically built for small applications but have a comparatively higher power density and cell efficiency at a higher cost. SOEC, operating at high temperatures, are at an early stage of development with potential advantages of high electrical efficiency, low material cost and the ability to operate in reverse mode as a fuel cell or in co-electrolysis mode, producing synthetic gas from water steam and CO_2. Although electrolysis is an endothermic reaction, heat transfer losses usually occur as a result of waste heat that can be used in other applications.

Synthesis of methane, other hydrocarbons or ammonia

The production of synthetic gaseous or liquefied hydrocarbons in the following process steps after electrolysis requires various additional reactor systems, such as a metanation reactor (catalytic reactor or biological reactor), the Fischer-Tropsch catalytic reactor or a methanol synthesis reactor, which also can be used in combination with a further process for the production of oxymethylene ether (OME). In these reactors CO_2 is a raw material, in addition to hydrogen. During the completed P2X chains, each step of the process is associated with energy losses: typical efficiencies for the production of electricity-based synthetic fuels range from 20% (OME) to about 40% (methane). Depending on the thermodynamics of the processes, improved efficiency can be achieved if the waste heat (e.g. from the methanization reactor) is used to heat other processes within the P2X system.

3. Power-to-H_2 technologies

This section describes the different technologies for the production of hydrogen, starting with Power-to-H_2 technology (i.e. different types of water electrolysis) and then explaining the conventional technologies.

3.1. Technical and economic parameters

Power-to-H_2 is a chemical process that produces synthetic hydrogen using electricity. Water electrolysis is currently the main technique to achieve this process: H_2O is broken down into H_2 and O_2 using electricity. There are 3 techniques for achieving this process: alkaline electrolysis, proton exchange membrane electrolysis (PEM), and solid oxide electrolysis cell (SOEC).

In addition, all three technologies, and especially SOEC, can be upgraded by leading the process of electrolysis at high temperatures, which will increase the efficiency of the process. However, as high temperature electrolysis and SOEC are not currently mature, there are still no technical and economic projections for these technologies. As a consequence, low temperature alkaline technology and PEM technology are the only two technologies whose data are analyzed in detail for Power-to-H_2.

The cost of producing H_2 depends on four key parameters: service life, energy conversion efficiency, capital costs (CAPEX) and operating costs (OPEX).

Alkaline electrolysis

The following reactions occur in this process:

- Anode - $2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$ (3.1.1)

- Cathode - $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ (3.1.2)

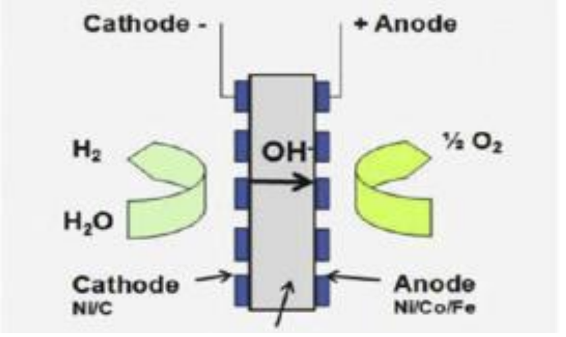

Fig. 2 Illustration of the principle of operation of a cell for electrolysis of alkaline water
Source: METIS Studies: The role and potential of Power-to-X in 2050

Table 1. Advantages and disadvantages of alkaline electrolysis

Advantages	Disadvantages
Currently the cheapest electrolysis technology;	Low margin of improvement of CAPEX;
Fast response time enables provision of services of the power system (i.e. flexibility);	Dangerous corrosive electrolyte.
Longer life than PEM;	
High purity of hydrogen (some consumers have high standards of purity quality, such as the transport sector).	

Source: METIS Studies: The role and potential of Power-to-X in 2050

PEM electrolysis

The following reactions occur in this process:

- Anode - $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ (3.1.3)
- Cathode - $2H^+ + 2e^- \rightarrow H_2$ (3.1.4)

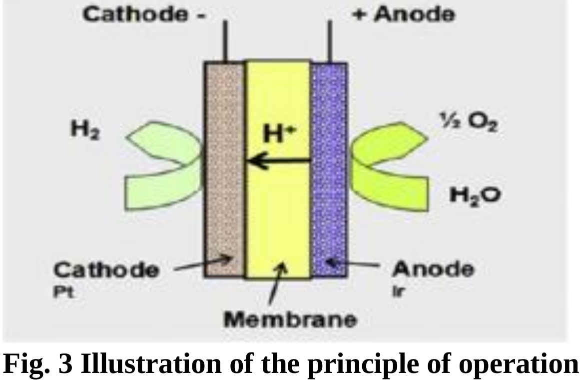

Fig. 3 Illustration of the principle of operation of a PEM cell for water electrolysis
Source: METIS Studies: The role and potential of Power-to-X in 2050

Table 2. Advantages and disadvantages of a PM electrolysis

Advantages	Disadvantages
The absence of electrolyte allows easy handling of the technology compared to alkaline;	Use of precious metals (depending on costs);
Compactness, easy production;	Less mature than alkaline technology: not yet commercial on a large scale (higher CAPEX).
Less impact from input conditions;	

Fast response time to flexibility;	
High purity of hydrogen.	

Source: METIS Studies: The role and potential of Power-to-X in 2050

SOEC electrolysis

The following reactions occur in this process:

- Anode - $2O^{2-} \rightarrow O_2 + 4e^-$ (3.1.5)
- Cathode - $2H_2O + 4e^- \rightarrow 2H_2 + 2O^{2-}$ (3.1.6)

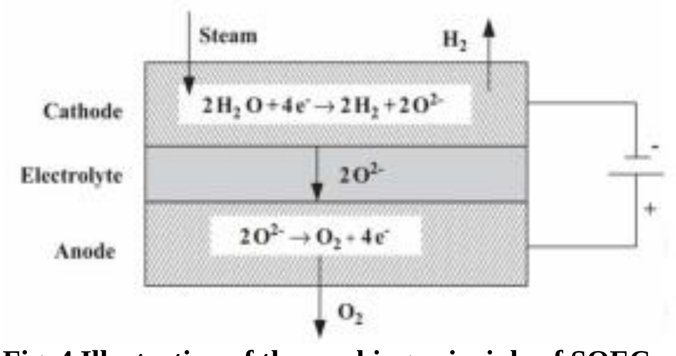

Fig. 4 Illustration of the working principle of SOEC
Source: METIS Studies: The role and potential of Power-to-X in 2050

Table 3. Advantages and disadvantages of a SOEC electrolysis

Advantages	Disadvantages
Better efficiency than other technologies;	Far from commercial;
Can be combined with other heat recovery processes at a low cost.	Less flexible than other technologies and unsuitable for intermittent operation.

Source: METIS Studies: The role and potential of Power-to-X in 2050

3.2. Alternatives for hydrogen production

In addition to electrolysis of water, H2 can be produced by alternative techniques such as: Steam Methane Reforming (SMR), Partial oxidation of fossil energy; Autothermal reforming: a combination of steam reforming and partial oxidation; Gasification of coal; Biomass gasification; Thermochemical cycles; Photocatalytic separation of water; Photo-biological separation of water; A by-product of the production of acetylene and olefins or refineries.

Assuming a high rate of decarbonisation in the gas sector and given current technological trends, the main competitor to Power-to-H2 will be SMR with CCS.

SMR/ SMR + CCS

SMR or steam methane reforming is a process in which methane from natural gas is heated by hot steam, in the presence of a catalyst, to obtain carbon monoxide and hydrogen used in organic synthesis and as a fuel.

CSS is the process of capturing waste carbon dioxide, transporting it to a storage site and depositing it where it will not enter the atmosphere.

SMR Method:

The following reaction occurs first:

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO \tag{3.2.1}$$

Then, elimination of CO:

$$CO + H_2O \leftrightarrow H_2 + CO_2 \tag{3.2.2}$$

The result is:

$$H_2 + CH_4 + H_2O + CO_2 \tag{3.2.3}$$

and finally purification.

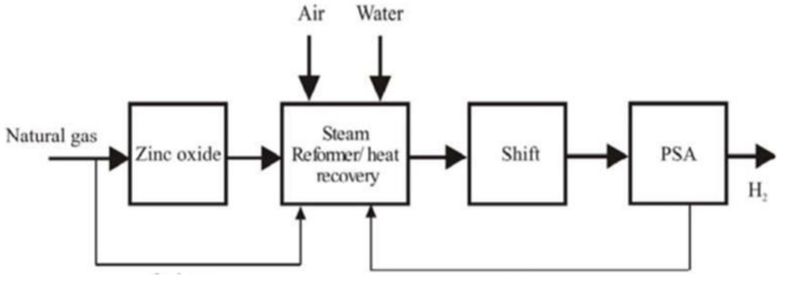

Fig. 5 Block diagram of hydrogen flow through methane steam reform
Source: METIS Studies: The role and potential of Power-to-X in 2050

Table 4. Advantages and disadvantages of SMR + CCS

Advantages	Disadvantages
SMR offers an efficient, economical and widely used hydrogen production process.	SMR is dependent on the price of natural gas and the price of carbon dioxide;
	CCS is not currently commercially available;
	The development of SMR + CCS depends on the progress of CCS and its ability to integrate into SMR plants.

Source: METIS Studies: The role and potential of Power-to-X in 2050

The SMR + CCS configuration has more significant costs (CAPEX and OPEX) than the simple SMR process. However, the CCS component can be cost effective if the cost of carbon and the number of hours at full load are high enough. In order to determine the break, the production costs (variable price + investment price) for both technologies are calculated. Production costs are calculated using the following equations:

$$productionCost(SMR) = \frac{annualisedCapex(SMR) + Opex(SMR)}{LoadHours} + CH_4Cost(SMR) + CO_2\,Price(SMR) \tag{3.2.4}$$

$$productionCost(SMR+CCS) = \frac{annualisedCapex(SMR+CCS) + Opex(SMR+CCS)}{LoadHours} + CH_4Cost(SMR+CCS) \tag{3.2.5}$$

4. Power-to-CH_4 technologies

4.1. 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 to produce methane.

Carbon dioxide methanation can be described by the following reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{4.1.1}$$

This reaction can occur through two different techniques: catalytic methanation or biological methanation.

Catalytic methanation

The catalytic reaction takes place inside the reactor in the presence of a catalyst such as nickel, rhodium or ruthenium, and nickel is more commonly used due to its low cost. Two types of reactors can be used: adiabatic reactor and isothermal reactor. There is no heat exchange between the adiabatic reactor and the reaction fluids resulting in an increase in temperature inside the reactor. The isothermal reactor includes a cooling circuit that allows heat to be dissipated and the temperature in the reactor to be controlled.

The reaction that takes place inside the reactor is as follows:

$$CO_2 + 4H_2 \rightarrow CH_4 + H_2O \tag{4.1.2}$$

Table 5. Advantages and disadvantages of catalytic methanation

Advantages	Disadvantages
Technology well known in the industry;	Temperature control inside the reactor is required: high temperature can damage the catalyst;
Efficiency can be improved by returning the high temperature released during the reaction.	Longer response time than electrolysis.

Source: METIS Studies: The role and potential of Power-to-X in 2050

Biological methanation

The biological way is a new technology that uses methanogenic microorganisms that act as bio-catalysts. The reaction takes place under anaerobic (oxygen-free) conditions inside the so-called digester where there are two possibilities of process. Either H_2 is added directly to CO, initially stored in the digester by microorganisms or H_2 is first mixed with CO_2, then the aggregated gas is sent to a water-filled digester containing the microorganisms.

Both methanation processes require a reliable source of CO.

- Operating temperature: between 35 ° C and 65 ° C depending on the type of microorganisms;

- Operating pressure: atmospheric pressure (1 bar);

- Methane rate in the exhaust gas: 98-99%;

- Efficiency: 78-80%;

- CAPEX: 1000 € / kW (for methane);

- OPEX: ~ 12% (capex);

- Flexibility: time of induced increase from 0 to 90%.

Table 6. Advantages and disadvantages of a biological methanation

Advantages	Disadvantages
Simple technology;	It is not yet mature technology;
No catalyst;	pH control inside the digester.
High purity of methane output;	
Better response time than catalytic methanation;	
Raw biogas can be used as a source of carbon dioxide (depending on the type of digester);	
Significant cost reductions are forecasts by professionals in the coming decades.	

Source: METIS Studies: The role and potential of Power-to-X in 2050

4.2. Alternatives for methane production

Methane production is currently dominated by fossil natural gas, with only a small proportion coming from biogas. Biogas refers to a mixture of different gases produced by the decomposition of organic matter (biomass), mainly methane and carbon dioxide, and secondarily H_2 (hydrogen), O_2 (oxygen), H_2S (hydrogen sulfide) and N_2 (nitrogen). After further purification, biogas becomes biomethane which has the same quality as natural gas and whose production has increased significantly in recent years. Unlike biogas, biomethane can be used in vehicles and injected into the gas network.

Biomass-to-CH_4 (biomethane) has two main production techniques: anaerobic digestion and thermal gasification. Similar to biological methanation, anaerobic digestion carries out a series of biological processes in which microorganisms decompose into biodegradable material in the absence of oxygen. The process results in digest (decomposed material) and biogas (mainly CH_4 and CO_2). To obtain biomethane, biogas must be added to methane by removing carbon dioxide (through a so-called purification process).

During thermal gasification, the thermal decomposition of wood biomass and consumer waste takes place in a gasifier, in the presence of a controlled amount of oxygen and steam. As a result of synthetic gases (containing CO, CO_2, H_2 plus pollutants such as sulfur and chlorides) it is purified and upgraded to biomethane thanks to the methane metering unit (as a catalytic methane for power-to-methane).

As for the production of H_2, the main competitor for the production of Power-to-CH_4 should be evaluated. Assuming a high cost of carbon dioxide, it is likely that Power-to-CH_4 will have to compete with Biomass-to-CH_4 as a carbon dioxide neutral alternative.

5. Power-to-Liquids technologies

5.1. Technical and economic parameters

By following the process of electrolysis of water, synthetic hydrogen can be converted to various liquid fuels such as diesel, ethanol, methanol, dimethyl ether or ammonia-like fuels. Each fluid has its own conversion process. In the remainder of item 5, the focus is on diesel /

gasoline-like fuels generated through Power-to-Liquids process chains, for two main reasons. First, these fuels are produced through Fischer-Tropsch synthesis or methanol synthesis, which are the most experimented processes of Power-to-Liquids and are thus characterized by the highest availability of data in terms of technical and economic parameters. Second, these fuels are likely to experience significant use in the future because of their ability to replace fossil fuels in specific segments of the transport sector where electric batteries or fuel cells can only be used to a limited extent, such as aviation.

Production of liquid fuels through Fischer-Tropsch synthesis

The Fischer-Tropsch process produces various hydrocarbons through the main reaction:

$$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O \qquad (5.1.1)$$

n is usually 10-20, resulting in crude liquid fuel being refined.

Other types of reactions occur inside the reactors. Carbon monoxide is obtained from carbon dioxide by using a reverse reaction to change water and gas.

Table 7. Advantages and disadvantages of Fischer-Tropsch synthesis

Advantages	Disadvantages
Relatively established technology, because it is already used for processes for conversion of coal into liquids	It is not yet fully mature technology for power conversion processes into liquids.

Source: Source: METIS Studies: The role and potential of Power-to-X in 2050

Production of fuels through the synthesis of methanol

The reaction for methanol synthesis is as follows:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \qquad (5.1.2)$$

- Methanol can also be produced by the reaction of H_2 and CO.

- Methanol can be supplemented by further conversion to synthetic gasoline, diesel or monomolecular fuels such as OME (oximethyl ether) or DME (dimethyl ether).

Table 8. Advantages and disadvantages of synthesis of methanol

Advantages	Disadvantages
The synthesis of methanol is a known process, but the raw materials are natural gas or coal.	There is currently no mature technology for Power-to-Liquids.

Source: Source: METIS Studies: The role and potential of Power-to-X in 2050

5.2. Alternatives for fuel production

Biofuels can be considered the most advanced sub-category of Biomass-to-Liquids conversion technologies. Among biofuel technologies, first-generation biodiesel and bioethanol are currently the most developed, but they have limited growth due to their competition with the food industry and their limited carbon emission benefits. Considering advanced biodiesel as a major competitor to Power-to-Liquids conversion technology seems to be increasingly relevant as Power-to-Liquids fuels should not be mixed with other fuels (they can be used directly in ICE).

6. Fields of application for Power-to-X projects

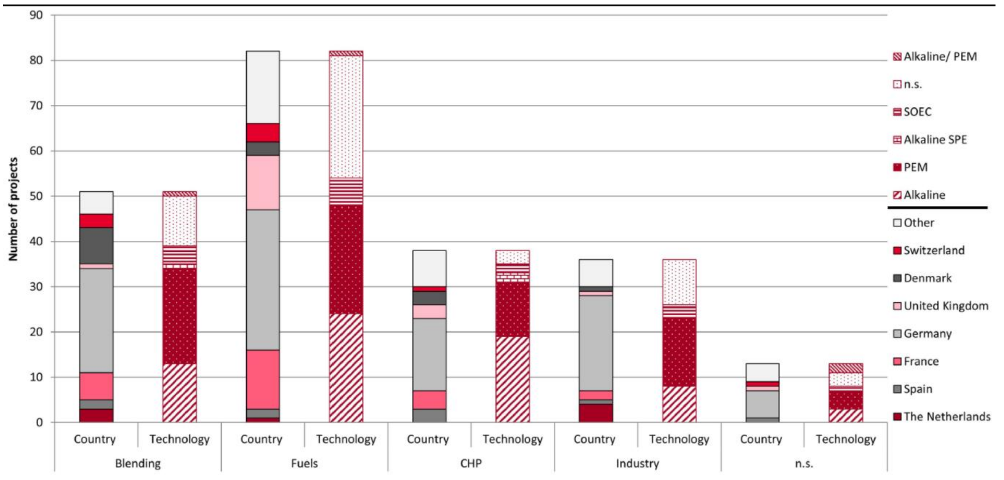

Fig. 6 Fields of application for Power-to-X projects according to countries and technologies. Source: Demonstration Projects in Europe. Institute of Energy and Climate Research – Systems Analysis and Technology Evaluation

As can be seen in figure 6, in the context of fuel production, PtX is the most common field of application in Europe with a 37% share of all projects. As it can be seen from figure 6 certain types of electrolyzer are preferred for different fields of application. For CHP purposes, an alkaline electrolyzer is used in almost 50% of the projects, whereas for industrial applications, a PEM electrolyzer is used in 47% of the projects. However, the use of industrial applications and PEM electrolyzers has increased significantly in recent years.

Conclusions

The development of P2X technologies is progressing quickly and will continue to do so in the near future due to its characteristics, applications and impact on the environment. The development of PEM and alkaline electrolyzer technologies has been good and these technologies are used very often, although there seems to be an apparent preference for the more mature alkaline technology in the future. Solid oxide electrolyzer cells are catching up in their technological development with multi-MW projects. Methanation is used in many applications and has proven its feasibility for hydrogen processing. As for the production of liquid fuels, it is safe to say that it is the fuel of the future. As much effort as possible should be made to utilize this technology, which will contribute to saving the planet from pollution.

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