Electricity as a part of production costs in Power to X technologies

Lappeenrannan–Lahden teknillinen yliopisto LUT

Tuotantotalouden kandidaatintyö

2023

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TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Teknis-luonnontieteellinen

Tuotantotalous

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Sähkö osana tuotantokustannuksia Power to X teknologioissa.

Tuotantotalouden kandidaatintyö

2023

38 sivua, 7 kuvaa ja 3 taulukkoa

Tarkastaja: Yliopisto-opettaja Tiina Sinkkonen

Avainsanat: Power to X, Power to gas, Power to liquid, Power to food, Tuotantokustannukset, Sähkö

Teollisuudesta ja tuotannosta johtuvat päästöt ovat yksiä ilmastonmuutoksen pääaiheuttajia. Joitain tuotannon ja teollisuuden prosesseja voitaisiin korvata päästöttömillä Power to x teknologioilla. Nämä teknologiat ovat kuitenkin pääasiassa kalliimpia tuotantotapoja suuren sähkön kulutuksen ja huonon hyötysuhteen takia.

Työssä tarkastellaan sähkön osuutta P2X teknologioilla valmistettujen tuotteiden tuotantokustannuksissa. Lisäksi tarkastellaan P2X:n kustannuskilpailukykyä vaihtoehtoisiin tuotantotapoihin nähden ja tulevaisuuden odotuksia.

Työssä havaittiin, että sähkönosuus P2X:n tuotantokustannuksista on suuri, likimain 60%. Tämä on huomattavasti enemmän kuin vaihtoehtoisilla tuotantomenetelmillä. Suurimmat sähkönkuluttajat ovat elektrolyysi ja metanaatio, niiden huonon hyötysuhteen vuoksi. Viime aikojen energiakriisillä ei ole näyttänyt olevan negatiivisia vaikutuksia P2X:n tuotantoon. P2X:n tuotanto kustannukset ovat huomattavasti kalliimmat tällä hetkellä, kuin vaihtoehtoisilla tuotantotavoilla. Tästä huolimatta P2X-teknologioiden tulevaisuus näyttää tuotantokustannuksia tarkasteltaessa hyvältä, sillä uusiutuvan energian hinta tulee todennäköisesti laskemaan ja nykyisten P2X-prosessien hyötysuhde paranemaan.

ABSTRACT

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Electricity as a part of production costs in Power to X technologies

Industrial Engineering and Management's bachelor's thesis

2023

38 pages, 7 figures and 3 tables

Examiners: University teacher Tiina Sinkkonen

Keywords: Power to X, Power to gas, Power to liquid, Power to food, Production cost, Electricity

Emissions resulting from industry are one of the main causes of climate change. Some industrial processes could be replaced by emission free Power to X technologies. How ever these technologies mainly more expensive methods because of high electricity consumption and poor efficiency.

This thesis studies electricity as a part of production costs in Power to X technologies. Additionally cost competitiveness against conventional methods and future aspects are examined.

Electricity cost from total production costs are high, approximately 60%. This is significantly more than conventional production methods. Greatest electricity consumers are electrolysis and methanation, due to their poor efficiency. Energy crisis has not affected negatively to P2X technologies. At the moment P2X technologies are more expensive than conventional processes. Nevertheless the future of P2X technologies looks promising when considering production costs, as the price of renewable energy is likely to decrease and the efficiency of P2X processes improve.

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1 Introduction

This thesis focuses on Power to X technologies. Thesis also reveals what kind of impacts electricity costs have in P2X technology's production costs and cost-competitiveness against current conventional processes.

1.1 Background

World's energy and food needs are increasing because of constant population growth. At the same time climate change is getting worse and emissions from both energy and food production have huge impact on that. (International Energy Agency 2022.) Emission from industry are also high (European Council 2023). That is why it's important to find more sustainable solutions to these industries. Some of these industry processes could be done with emission free P2X technologies. (Ince et al. 2021)

1.2 Objectives and research questions

This study's objective is to illustrate the total production costs and the share of electricity costs in chosen P2X technologies. Additionally cost competitiveness against conventional technologies and future aspects of P2X are studied. P2X technologies are distributed to Power to heat, Power to gas, Power to liquid and Power to food. This thesis is done in co-operation with Solar Foods, which produces protein with P2X, and therefore it is used as a case example of Power to food.

This study's research questions are:

Q1: What is the impact of electricity costs on the overall production costs of Power-to-X and conventional fossil-based technologies.

Q2: How does electricity cost effect to cost-competitiveness?

1.3 Methods and defining

This study is performed by using search services, search engines and databases for peer reviewed scientific documents.

Table 1: Thesis most important tools and search terms

Tools	Most important keywords
Primo Google Scholar Scopus	Power to X Power to gas Power to liquid Power to food Production cost Power to methane Power to ammonia Power to methanol Water electrolysis

Table 1 represents this thesis most important tools and keywords. LUT organization's own Primo search service was the main service used. Additionally some information was provided from web search engine Google Scholar and Scopus database.

P2X technologies are defined to power to methane, - methanol, -ammonia and -food. Keywords are strongly related to these. Other P2X technologies are not taken into account, since these are examples of Power to liquid, Power to food and Power to gas, which are main research objects. Energy production and energy crisis is only observed in Europe.

1.4 Structure

This thesis has 6 main chapters. First one is introduction chapter that involves study's background, objectives, methods and structure. In second chapter we focus on P2X's theoretical literature. It includes process descriptions and feasibilities for used P2X technologies. Since P2X technologies need renewable energy and a lot of electricity, electricity prices, production and ongoing energy crisis is viewed in chapter 3. Chapter 4 is for Case Solar Foods

which is an example of newer Power to food technology. Chapter 4 will focus on electricity consumption, process and production costs of power to food technology. Chapter 5 focuses on the total production costs and electricity costs of power to x and conventional technologies. In chapter 5 total production costs and electricity costs of power to x and conventional technologies are formed. These results and cost competitiveness are compared between one another. Also, future prospects are evaluated and viewed. Chapter 6 consists of study's results, answers to research questions and ideas for further research.

2 Power to X

P2X is a method to convert renewable energy into liquids, gases and heat without carbon dioxide emissions (Ince et al. 2021). Also newer Power to food technology has been developed (Solar foods 2023a). P2X system uses a lot of hydrogen and carbon dioxide (CO_2). Usually, hydrogen is separated from water with electrolysis using renewable energy source. Carbon dioxide can be separated from air, biogas or flue gas. By combining hydrogen and carbon dioxide sustainable products can be made. P2X systems was first proposed in 1994 by Koji Hashimoto to synthetic methane production. (Ince et al. 2021.)

2.1 Power to Hydrogen

Figure 1 represents P2X's main working method. Every P2X process follows this formula. Everything floats around water electrolysis, because from there process gets its main raw material, hydrogen. Electricity is from renewable energy sources. After electrolysis next phase is synthesis. (Rueter 2019) This is mainly same for all processes with small personalization for every P2X method (Technical University of Denmark 2023). Synthesis may also contain different raw material inputs than just CO_2, as we will later discover. In the next chapters we are going to orient to couple of P2X's processes.

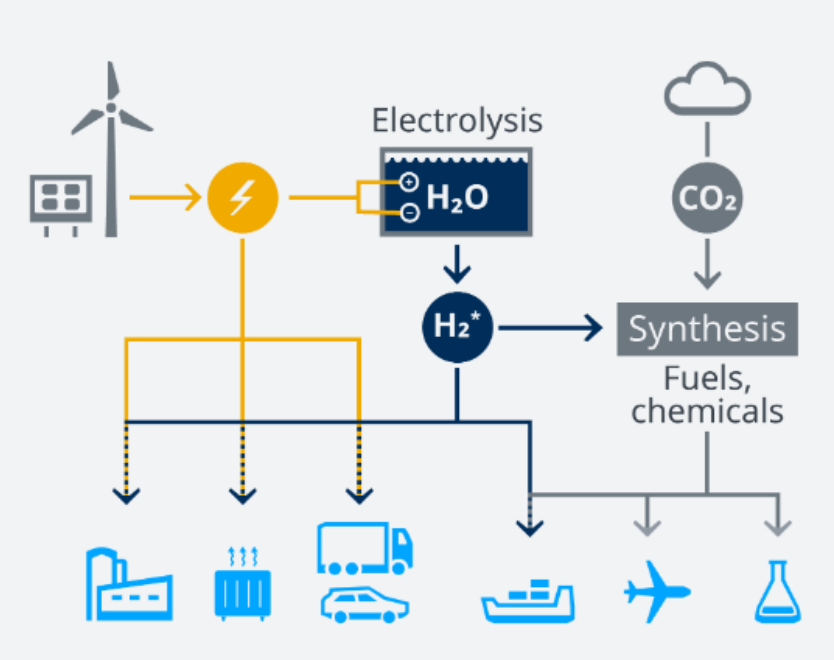

Figure 1: Power to X Route (DW 2023)

Hydrogen (H_2) is a gas that is generally used in oil refining and in production of ammonia (IRENA 2019). In P2X it serves another purpose. Hydrogen's production is important for P2X processes because it is needed in every process. Hydrogen is produced via water electrolysis. Water electrolysis is one of the environmental friendliest ways to get hydrogen if energy used is from a renewable energy source. Water electrolysis doesn't imply carbon emission to the atmosphere. Also it produces very few other end-substances. (Sorrenti et al. 2022.) Electrolysis is a process where electric current is passed through a substance to result in chemical change in substance. Basic idea of electrolysis is that pure water is placed in electrochemical cell and it has two electrodes connected to external power supply. External power supply starts to flow at the certain voltage. The electrodes start to produce hydrogen (H_2) at the negatively biased electrode and oxygen (O_2) at the positively biased electrode. Water electrolysis reaction equation is:

$$H_2O\ (l) \rightarrow H_2\ (g) + \frac{1}{2}O_2\ (g) \qquad (1)$$

Reactions enthalpy change ΔH is +285.840 kJ/mol on standard temperature and pressure (Zoulias, et al. 2004.). Because enthalpy change is positive, reaction is called endothermic and it absorbs heat. Because enthalpy change is so high, process needs a lot of energy in order to work. Electrolysis efficiency is at the moment about 60-70% (Gorre et al. 2019;

Agora Verkehrswende et al. 2018). So at the moment power to hydrogen is quite expensive and inefficient, but vital for P2X technologies.

2.2 Power to Ammonia

Ammonia (NH_3) is mostly used as a fertilizer in agriculture. Small amount is used in various industrial applications, such as plastics, synthetic fibers and explosives. (International Energy Agency 2023b.) Studies has shown that ammonia can also be used as a fuel on engines (Sorrenti et al. 2022; Tornatore et al. 2022). Ammonia is really potential energy source, because it has high energy density and it is easy to storage. Couple of ammonia using engines are already in the making. (Sorrenti et al. 2022.) Current ammonia production causes huge carbon dioxide emissions to the environment. Because production uses a lot of fossil energy source, it is highly depended on the fossil energy sources. (Ince et al. 2021)

If renewable energy source's development and usage continues its growing favor, it's inevitable to make changes to engines in order to support more sustainable energy sources. Power to ammonia's reaction equation is (Klyapovskiy et al. 2021):

$$3H_2 + N_2 \rightarrow 2NH_3 \quad (2)$$

Required nitrogen is usually separated from the air by process that consumes electricity. Also, energy is needed to compress the reaction to high pressure and to reaction's required high temperature. Hydrogen is obtained from electrolysis. Ammonia reactions enthalpy change ΔH is -91.8kJ/mol. Negative enthalpy change means that reaction is exothermic and it releases energy. (Klyapovskiy et al. 2021.)

2.3 Power to Methane

Methane (CH_4) is colorless, odorless and easily flammable gas. It is mainly used as fuel to make light and heat (Wisconsin department of health service 2023). Power to methane is example of Power to synthetic natural gas (P2-SNG) production. The methanation process can cover both gas (P2-SNG) and heat (P2H) demands, because of its working temperature is 200-400 Celsius and it is possible to extract and store this heat from the products. Working heat is also produced from electricity and because of this power to methane is process is

expensive. (Sorrenti et al. 2022.) Methane is one of the main raw materials used in a conventional fuel for heating and transportation (Skorek & Wlodarcyk 2018). Process of converting CO2 into methane is one of the most promising technologies for transforming electrical energy into renewable chemical energy (Hidalgo & Martin-Marroquin 2020).

It is possible to produce methane with couple of ways, but the basic method is the same. Inputs are hydrogen and carbon dioxide which are obtained from electrolysis and from air capture. Power to methane process's reaction equation is (Ghaib & Ben-Fares 2018.):

$$4H_2(g) + CO_2(g) \rightarrow CH_4(g) + 2H_2(g) \quad (3)$$

Hydrogen is produced once again from the water electrolysis. Carbon dioxide can be captured from several residual streams, for example generation and waste treatment facilities, biomass and cement plants or from surrounding air. Many of these processes generate CO_2 as a byproduct so it is really environmental friendly to use these residual streams. After collecting the processes inputs, methane is produced in chemical methanation using metal catalyst which is supported by metal oxides (Hidalgo & Martin-Marroquin 2020). Methanation process consumes a lot of electricity and its efficiency is usually about 70-87% (Lisbona et al. 2020; Blanco et al. 2018).

2.4 Power to Methanol

Methanol (CH_3OH) is an alcohol, which is used largely as other product's raw materials. For example methanol can be used in inks, resins, acetic acid and dyes. (ChemicalSafetyFacts 2022) Also, methanol can be used as a fuel. Methanol has been produced mainly from obtained syngas from the reformation of natural gas or coal gasification. These methods release significant amount of carbon dioxide emissions. Because of this renewable methanol production process has gained great attention. (Colpan et. al 2021.)

Reaction equation (Smith et al. 2019):

$$CO(g) + 2H_2(g) \rightarrow CH_3OH\ (l) \quad (4)$$

Methanol is example of Power to liquid. There are 3 main steps in power to methanol production: electrolysis, air capture and methanol synthesis. Electrolysis output is hydrogen and air captures output is CO_2. Conventionally CO_2 can also be obtained from other sources as shown in previous Power to Methane chapter 2.3. CO_2 can be electrolyzed to formation of

CO. These are the inputs to methanol synthesis. In methanol synthesis hydrogen and CO are pressurized and heated up to 240 Celsius. Inputs react together and combine to produce methanol. (Bos et al. 2020.)

3 Electricity markets

We have noticed from the former chapter 2 that every P2X process consumes a lot of electricity. Main electricity consumers are synthesis and water electrolysis. Energy prices have climbed from 2020 and prices have been really high for couple of years (Europa 2022). In this chapter we are going to go through electricity production, price formation and reasons for electricity price rise.

3.1 Electricity production

Figure 2 represent electricity production development by source in Europe. In 2020 most of the electricity was produced by nuclear and natural gas. Coal was dominating the electricity production from 1990 to 2015, but since then its production has been decreasing. Hydro energy has continued its steady climb in the 21st century. Other renewable energy sources have grown the most since 2010. The biggest riser has been wind energy. It has more than doubled its production in the 2010s.

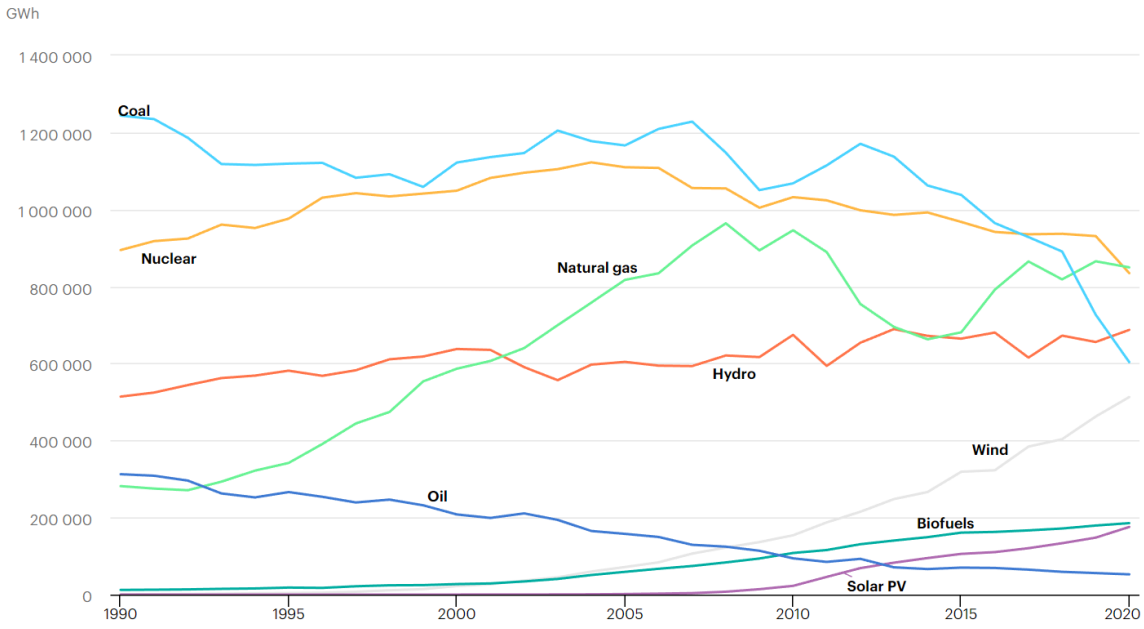

Figure 2: Electricity generation by source in Europe (International Energy Agency 2023a)

Reason to renewable energy's rise and decrease of coal energy is green transition and higher carbon dioxide emission compensation brought by it (Szczygielski et al. 2022). Green transition started in 2015 when Paris agreement was done. Paris agreement is legal agreement between participating countries to take actions against climate change. The agreement includes greenhouse gas emissions reduction with long term strategies and technology development strategies. (UNFCCC 2023)

3.2 Electricity price formation

There is couple of ways to buy electricity: spot and forward market. Mainly electricity price depends on supply and demand, if demand is greater than supply, electricity prices go up. Usually companies can buy electricity cheaper, because usually they are taxed less. For example some countries have policy that electricity bought by company does not include value added tax (VAT) at all. (EnFormer 2022.) Consumers pay from electricity according to how much they are using energy (kw) in certain period of time (h). Electricity retail price is so in kwh formation. Also, consumers pay for electricity transmission, taxes and levies (Rinaldi 2022.)

Spot market

On spot market electricity prices formation depends on three main participants: producers, sellers and consumers. Market prices move depending on these factors. In European union there is a so called "uniform price" rule. This means that electricity demand is first satisfied by technology whose production costs are lower. These technologies are usually the ones which are hard to store, such as nuclear and renewable energy sources. Uniform price rule allows lower electricity price for consumers when it is possible. If these energy sources are insufficient to meet the total electricity demand, other energy suppliers are put into service. The final price of electricity is largely related to production costs of the most expensive energy technology that enters the market supply. (Tehrani et al. 2022.) Market price formation is illustrated in figure 3. This pricing systems benefits the most energy that is produced with lower costs, because they still can sell energy with according to the most expensive technology used.

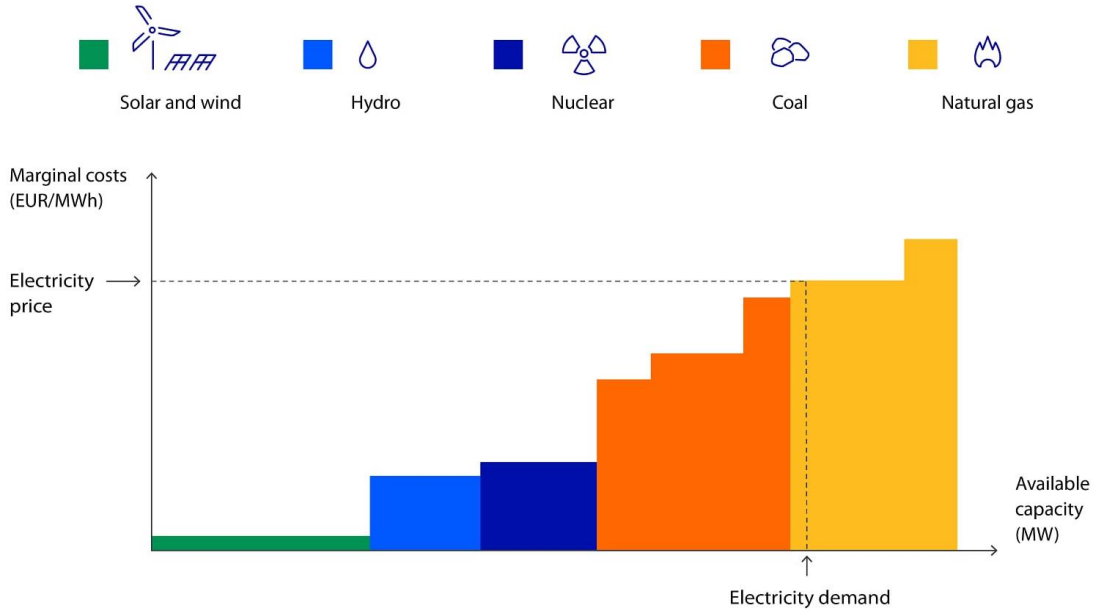

Figure 3: Electricity price formation (De Boer & Stet 2022)

Forward market

A large portion of electricity is also bought in advance, before the electricity is generated. This is called forward market and its conventional way to trade electricity. In forward market contracts kwh has a solid price, which is based by the current spot market price and forecasts for futures prices. Contracts can be done for the next months or years. Electricity suppliers, power plant operators and large consumers such as companies use this method to make forecasting the energy costs easier. (En:Former 2022)

As we can see from the figure 4 electricity price have been rising from 2008. The biggest rise has happened from 2020 to 2022. In 2020 electricity price was approximately 21 €/100 kwh and in 2022 the price was 25.3 €/100kwh. The percentage increase is then 20,5 % in just couple of years.

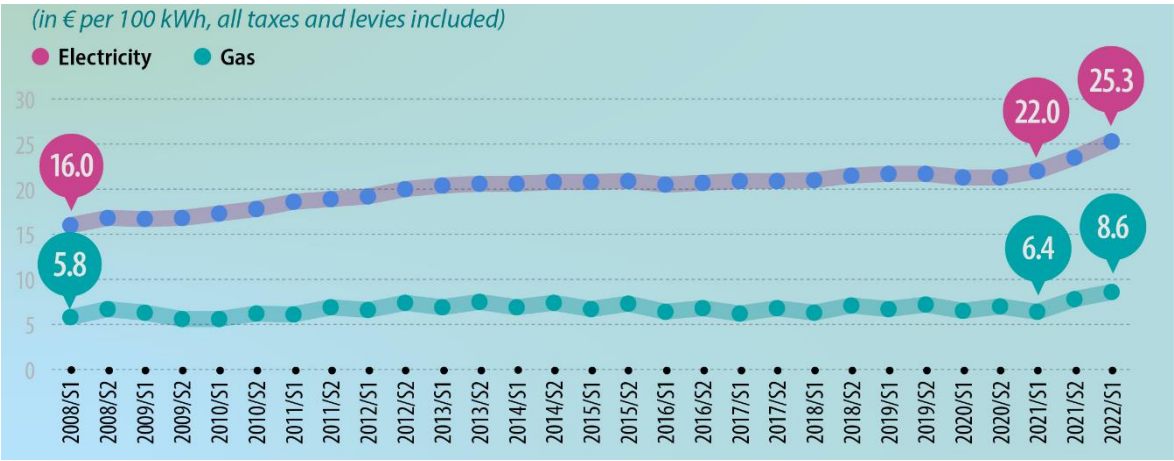

Figure 4: Electricity price evolution in the EU (Europa 2022)

3.3 Power to Heat

Overall electricity price has been rising, but P2X uses only renewable energy. Figure 5 presents price evolution of solar and wind power produced in different ways. This is also example of power to heat, since power to heat is basically electricity from renewable energy source which is converted to heat (Bloes et al. 2018), as we can also see from figure 1.

From the figure 5 we can see that the renewable energy sources prices have decreasing a lot from 2010. The greatest decreases have happened in photovoltaic solar power (PV) and in concentrating solar power (CSP). Onshore and offshore wind's prices have been decreasing, but not with such pace as solar powers. Only 2021 prices are compared, because after that there is only information about wind power prices.

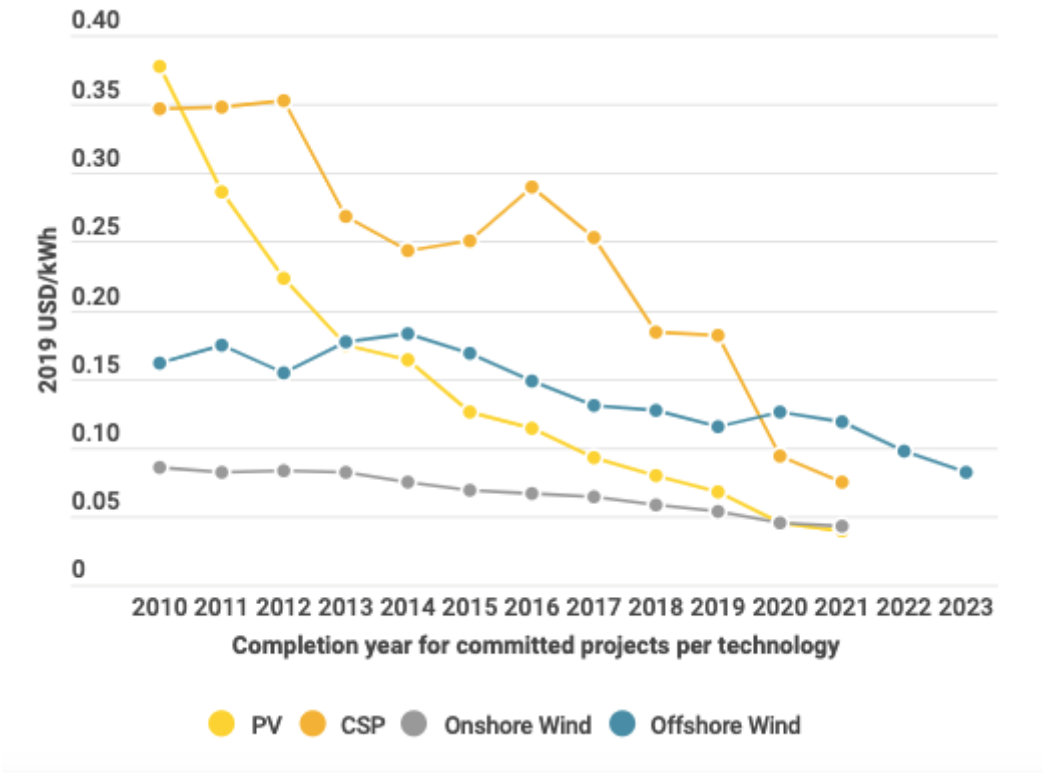

Figure 5: Evolution of wind and solar energy prices (International Renewable Energy Agency)

Average exchange rate from US dollar to euro in 2021 was 1.1829 (European Central Bank 2023). So 1 € equals to $ 1.1829. Highest renewable energy in 2021 was offshore wind at approximately $ 0,12 /kwh and the lowest were PV at $ 0,04 /kwh (Figure 5). When we divide these solar and wind powers average costs by exchange rate and multiply them by 100. We get 10,14€/100kwh for offshore wind and 3,38 €/100 kwh for PV. There is a huge price difference on what renewable energy source is used. Overall electricity price in 2021 were $ 22 – $ 23,5 /100kwh (Figure 4). So approximated average is 22,75 €/100kwh. Renewable electricity sources were about 55-85 % cheaper than conventional energy sources in 2021. So Energy crisis did not have effect on renewable energy sources electricity price.

3.4 Reasons to electricity price rise

Electricity prices have been rising a lot in past couple of years starting from 2020 (Figure 4). Europe was hit by energy crisis in the middle of 2021. There are couple of main reasons for electricity crisis: COVID-19 and Russia's war against Ukraine. When people were in

lockdowns because of COVID-19, they used much more electricity than was expected, because of that energy producers could not meet this demand. This resulted to electricity price rise. Also, later it was discovered that the main cause were the supply disruptions in the gas markets and the high volatility that gas is exposed to when trading. (Rinaldi 2022.) Russia started invasion to Ukraine and because of Western Europe's opposition to this, Russia limited gas supplies to Europe. These all combined resulted to electricity price rise. (Eurelectric 2023.) Russia's gas supply limitation resulted to a peak in natural gas price's pillar in Figure 3 and it made a huge gap between natural gas and coal prices. This means that energy prices were very dynamic and hard to predict.

Energy crisis has resulted to actions from European commission. They launched a process to reassess the whole electricity market's design and it is expected to come with a new legislative proposal in 2023. (Rinaldi 2022.)

When we look at the former figures 4 and 5 we can see that energy crisis has had little effect to renewable energy sources prices, since they have been decreasing. The energy crisis had more effect to overall electricity price and it has been increasing.

4 Power to Food, Case: Solar Foods

Power to X technology can also be used in food production (LUT 2022). We are going to use Solar foods as case example of power to food technology.

Solar Foods is a Finnish food technology company. It was born from scientific research held by VTT Technical Research Centre of Finland and Lappeenranta University of Technology. As a result, research team found out that electricity and CO_2 captured from the air can be used to develop calories or as they phrase it "growing food out of thin air". Dr Pasi Vainikka and Dr Juha-Pekka Pitkänen saw so much potential in this process that they decided to make this commercial. Solar Foods was founded in 2017. (Solar foods 2023a.) Solar Foods' goal is to be the first company to offer food products that are produced without agriculture or fossil fuels. Their products should arrive to markets in 2023 (VTT 2022.).

4.1 Process

Solar Foods has developed a way to produce protein called Solein. Solein is produced with fermentation, air and electricity. (VTT 2022) Fermentation is a process where substance is broken into smaller substances. Usually, microorganisms like bacteria are used in fermentation process. (Vocabulary 2023) Power to food process is similar to brewing beer or making wine (Solar Foods 2023c).

There is little information or studies regarding power to food process. However Solar Foods own web sites contain some information about the process. Power to food process consists of 5 steps: raw materials, natural bioprocess, harvesting, protein powder and food.

Main raw materials are single microbe, air, renewable energy and nutrients and minerals. Power to food uses direct air capture (Sillman et al. 2020) and main ingredients captured are CO_2, hydrogen and nitrogen. Renewable electricity is used in electrolysis to get hydrogen and also in the whole power to food process. A few other nutrients and minerals are used in the process. (Solar Foods 2023c.)

Microbe starts to multiply and grow to microorganisms in bioprocess, where microbe is fed with CO_2 and other nutrients. As the microorganism multiplies in the water the liquid starts

to get thicker, some of this slurry is harvested and dried up**.** (Solar Foods 2023c.) End product is Solein that consists of 65-70 % protein and which can be eaten as such or added to other food products. (Solar Foods 2023b; Solar Foods 2023c).

4.2 Production costs

Finnish Maaseudun Tulevaisuus journal (STT 2019) interviewed Solar Food's Chief Executive Officer Pasi Vainikka and Chief Technology Officer Juha-Pekka Pitkänen in their article. It appears from the article that power to food process uses 50 kwh of electricity per kg. So it is equivalent to 50000 kwh/ton and to 180 Gj/ton. For reference power to ammonia production uses 28-30 GJ/ton (Fasihi et al. 2021). Electricity consumption is significant in power to food production.

Pictet also interviewed Vainikka in their article (Mega 2021). It appears from the article that Solar foods has not yet started their full production, but they estimate that total production costs are between 5-6 €/kg or 5000-6000 €/ton. Since Solar Foods has not started their full production and it is assumed that renewable energy will continue decreasing, which was noticed in chapter 3.3, electricity price is determined to 5 cent/kwh. Then electricity costs equal to 2,50 €/kg. This means that 42-50 % of production costs goes to electricity costs.

4.3 Conventional protein production

In this thesis whey protein is used as an example of conventional food product, since it is quite similar to Solein powder. Whey is the liquid end subject of milk production. Whey protein can be produced in a couple of ways, depending on protein content but the main process is the same. (Navarro da Silva et al. 2015.) First the whey is cleaned from any unwanted impurities and fines with filtration. Then filtered whey is pasteurized where up to 90 % of the fat is removed. As a byproduct of this process, cream that contains at least 75 % of fat is created. Then becomes different types of concentration and purifying processes. (Navarro da Silva et al. 2015; Agora 2023.) End-product depends on these processes. Whey that consists 34 % of protein (Whey 34) uses ultrafiltration system that primarily filters protein. If one wants to make more protein-rich powder, a diafiltration process is needed. This way whey protein that consists at least 75 % of protein (Whey 80) can be produced. After these,

both whey go through couple of more steps to ensure that whey protein powder is pure and it does not consist too much moisture (Navarro da Silva et al. 2015.)

Overall production costs are greater the more protein-rich the end-product is. Energy is accountable for approximately 36 % in Whey 34 production and 55 % for Whey 80 production costs. Main energy used is steam. From these utilities approximately 7 % is for electricity in Whey 34 production and 25 % for Whey 80. So 2,5 % and 13,8 % of total production costs account for electricity costs. (Navarro da Silva et al. 2015.)

Since Solein consists of 65-70 % protein, Whey 80's values are used, because its protein richness is closer to Solein. Total production costs for Whey 80 are 12,468 R$/kg (Navarro da Silva et al. 2015). 1 R$ was equivalent on average to $ 0,2999 in 2015 (Exchangerates 2023) So, Whey 80's total production costs are $ 3,74 /kg and $ 3739 /kg

5 Techno-economical analysis

In former chapters we have inspected P2X's different processes and came to conclusion that every one of them need a lot of electricity in order to work. We have also inspected electricity markets evolution. Now we are going to view how electricity price has affected to P2X technologies. Also we compare costs and cost-competitiveness between P2X and its conventional process types by techno-economical analysis. Main focus is in electricity as a part of products production costs. Also future aspects are reviewed.

Techno-economical analysis is a method to analyze process, product or service. Typical outcomes are estimated capital costs, operating costs and revenues. These are usually done with software modelling. (Burk 2018.) This chapter forms estimation of electricity- and production costs using former studies and researches.

5.1 Electricity as a part of production costs

Agora Verkehrswende et al. (2018) states that in order to power to gas and power to liquid production to be economically viable, 2 conditions need to be fulfilled: High full load hours and low renewable energy prices. Full load hour means time that process is ongoing with full power in certain period of time. In order to production have high full load hours it needs to have good and efficient maintenance. (Pandit et al. 2023; Satymov et al. 2022.)

One of the main techno-economical factor in P2X is renewable energy, because in order to process to be called Power to X, the entire production process needs to be environmental friendly. Hydrogen production with electrolysis is costly because of the inefficient electricity use (LUT 2022). As we noticed in chapter 3.1 renewable energy sources cannot fulfill all the energy need, and because of that electricity prices rise to nuclear and coal levels in spot market. This means that if company is buying its electricity straight from the grid, electricity is more expensive most of the time than renewable energy source's electricity. Electrolyzer and methanation unit forms the largest portions of capital expenditure (CAPEX) in P2X and largest operating costs are formed form these because of the electricity consumption (Fambri et al. 2022).

Power to Methane vs conventional methane

Current information about electricity's share of total production costs was not found, but Gorre et al. (2019) have made a study focusing on production costs of methane in the future, in 2030 and 2050 to be precise. They found out that power to methane is highly dependent on electricity price. We can use their results for 2030 production costs as indicative values. Study shows that when electricity price is 50 €/MWh electricity share from total production costs is 72 %. When electricity price drops to 20 €/MWh electricity's share decreases to 50 %. At the moment electricity price is closer to 50 €/MWh so we are going to use study's equivalent value of 72 %. It's notable that Gorre et al. (2019) calculated their results with water electrolysis efficiency of 78 %. This is higher than current water electrolysis average as previously discussed in section 2.1. This means that electricity share can be even greater at the moment than 72 %. Total production costs for power to methane is $ 1380 /ton, according to IRENA (2019).

In this text, natural gas is referred to as an example of conventional method of producing methane, since Power to methane is example of power to synthetic natural gas as we noticed in chapter 2.3. Natural gas contains up to 98 % methane (Saha et al. 2016). Natural gas is a fossil-based energy source. It is drilled from the ground. Usually, oil and natural gas are produced together, so it is not feasible to separate their costs. These both are produced by rigs on top of water (Offshore) or drilling on land (Onshore) (EIA 2011).

Wells operating costs include energy costs. (EIA 2011) Oil and gas rig's main power sources are large diesel-fuel engines, also they have small electrical generator, which is also powered by fossil fuels (Freudenrich & Strickland 2023; Ipieca 2013). Electricity needed is produced with generators that also use diesel as an input energy (Freudenrich & Strickland 2023). Natural gas production uses diesel-fuel engines as a main power source and needed electricity consumption is therefore assumed to be negligible small. Therefore, diesel fuel's energy consumption share in production is used instead of electricity share.

We use a study from Fullenbaum et al. (2015) that evaluates oil and gas production costs. They used former data and information about other relevant studies and publications. Offshore's overall costs are higher, but it's mainly because of transportation costs, that are much greater than in Onshore production. So offshore's energy consumption and -costs are assumed to be the same as onshore. They found out that 15 % of total operating costs in onshore

goes to drilling and pumps and equipment consume 24 % of total costs. This equals to 39 %. These costs may include other costs such as maintenance, but the same way energy may be used in other areas than just the ones mentioned. So these costs are supposed to cancel each other out and energy costs from total costs is determined to 39 % of total production costs in conventional gas production. Total production costs are between $ 100 and $ 500 /ton (IRENA 2019).

Power to Methanol vs conventional methanol

International Renewable Energy Agency IRENA (2019) says in their research that power to methane production total costs are USD 800 to USD 1 600 per ton. Also, according to IRENA about 10-11 MWh of electricity is needed to produce one ton of methanol, most of it is for the electrolysis 9-10 MWh. Total costs were calculated with electricity price of 40 €/MWH. This means that electricity costs for 1 ton of methanol produced is 400-440 €/ton. So electricity costs are 25-55 % of total production costs. Same kind of results were received from Bos et al. research (2020) and from Fortes et al (2016). Research results were 613 €/ton and 980 €/ton.

Fossil-based Methanol is produced by further refining natural gas. About 60- 70 % of methanol's production costs are from feedstock of natural gas. Depending on the refining process additional electricity needed is approximately 0-10 %. (Arnaiz del Pozo et al. 2022.) We use the previously estimated energy share of natural gas production costs with a 5% increase. This equals to 40,95 %. Conventional methanol's total costs are between $ 100 and $ 400 /ton (IRENA 2019).

Power to Ammonia vs conventional ammonia

There is a lot of literature about Power to ammonia's economic analysis. For example Zhang et.al found out in their study in 2021 that minimum production costs is around $ 550 /ton with electricity price of 73 $/MWh. Comparable results were reported also by Ikäheimö et. al in 2018. They calculated that manufacturing costs of power to ammonia are between 431-528 €/ton when electricity price is 73 €/MWH.

With the best available technology at the moment, Power to Ammonia requires 28-32 GJ of electricity per ton of ammonia produced (Fasihi et al. 2021). Range depends on the efficiency of the electrolysis. About 85-90 % of the process energy demand comes from electrolysis. Remaining demand is for air separation to get carbon dioxide, hydrogen compression and for ammonia synthesis. Total average costs are $ 730 /ton for green ammonia globally, but it can vary from $ 400 /ton to $ 1670 /ton. Total costs depend on access to renewable energy sources and economic conditions. (Saygin et al. 2023.) When we reform average electricity consumption 30 GJ to MWH and multiply it with 73 €/MWh we get 608 €. So with 30 GJ of electricity consumption the electricity price for ton of ammonia is about 610 €/ton. This equals to 83 % for electricity costs from total production costs. In Saygin's study equivalent value was 72 %.

Conventional fossil-based ammonia production costs are between USD 175 and USD 810 per ton. This is based on gas price range of USD 1-15 /GJ. (Saygin et al. 2023.) IRENA (2019) suggests more optimistic production costs $ 200-350 /ton Global average price is then calculated to USD 470 per ton of ammonia. Saygin et al. also found out that conventional ammonia's energy costs account around 60 % of the total costs, which is formed from 45 % for gas and 13 % for electricity. 13 % electricity cost equals to USD 61 per ton from average production cost.

5.2 Summary of production costs

Table 2 can be assembled from previous chapters 4.2, 4.3 and 5.1. Euro to USD exchange rate average in 2023 was 1.074, so that is used in conversions (European Central Bank 2023).

Table 2: Total production costs comparison

Product	P2X production costs ($/ton)	Conventional production costs ($/ton)
Methane	1380	100-500
Methanol	800-1600	300-350
Ammonia	400-1670	175-810
Food	5370-6444	3739

As we can see from the table 2 these P2X technologies can be 2-3 times more costly than conventional production costs overall. Only cost competitive P2X product is ammonia at the moment. From P2X technologies studied, food is the most expensive product and second is ammonia. There is huge cap between them which can partly be explained by electricity consumption. As noticed in chapter 4.2 power to food uses 180 Gj/kg and ammonia uses about 30 Gj/kg.

Based on former 4.2, 4.3 and 5.1 chapters' main indicator numbers we can do a chart (Figure 6) to illustrate electricity as a part of production costs. This chart may not be precise, because P2X electricity consumption and costs varies on a lot of things such as electrolysis efficiency, electricity prices and technology used, but this chart gives a reference about the electricity share. All P2X processes include electrolysis electricity demand needed to produce hydrogen (Power to hydrogen).

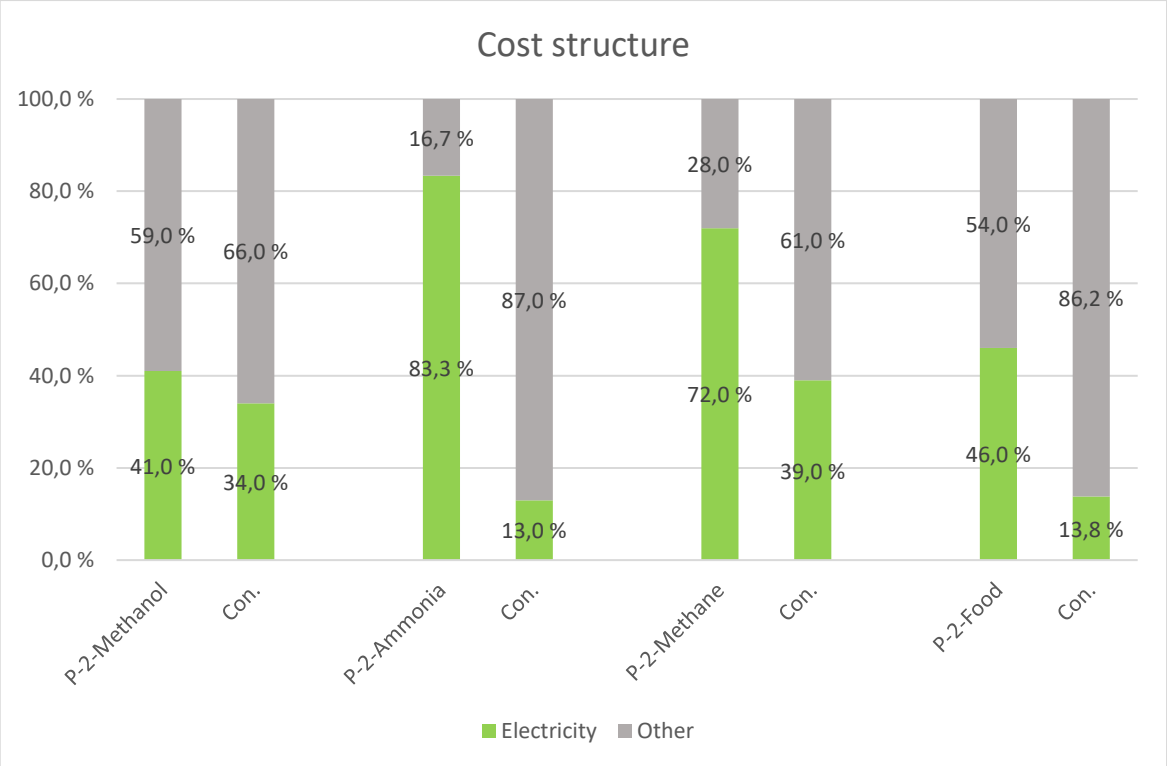

Figure 6: Electricity's share of total production cost

As we can see from the figure 6 electricity is a huge part of P2X technologies. Conventional technologies electricity costs are a lot smaller than P2X's. Since electricity is a huge part of cost structure, electricity price has a huge effect on these P2X production costs, but as we noticed in chapter 3 renewable energy prices have been decreasing. So actually, energy crisis

has effected more to conventional fossil-based production costs if they used spot market as an electricity purchase method.

5.3 Future

As we have noticed P2X is not cost competitive at the moment against conventional fossil-based products. Huge electricity consumption with low efficiency is the main reason to this. This may not be the case in the future.

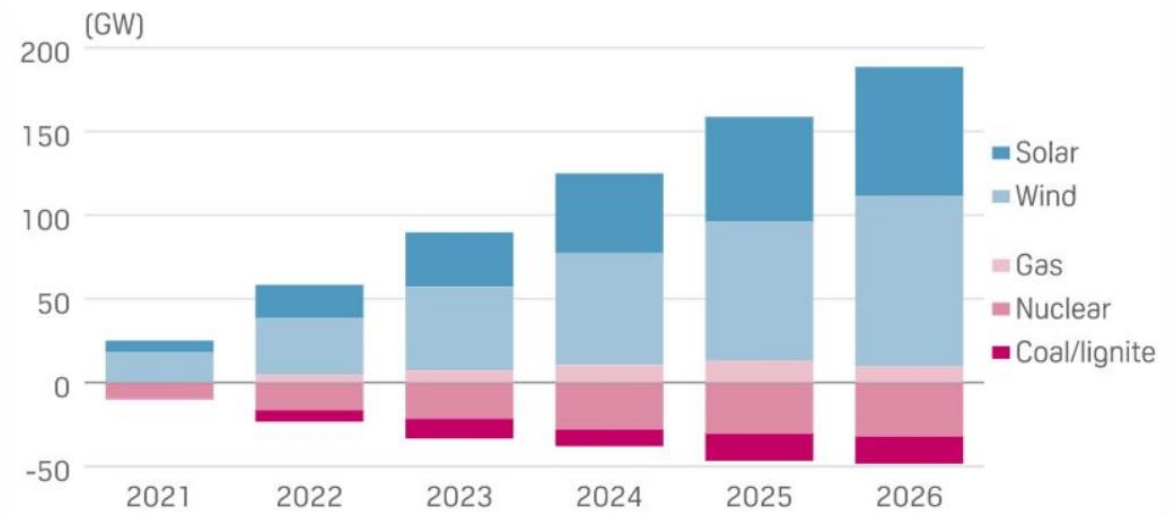

Figure 7:Electricity capacity growth (S&P Global Platts Analytics 2021)

Figure 7 illustrates futures capacity growth of energy in different categories in Germany, France, Great Britain, Italy, Spain and five smaller countries Portugal, Austria, Switzerland, Belgium, Netherlands (Franke 2021). As we can see from the figure renewable energy sources capacity growth is going to almost double in 2026 compared to present 2023. At the same time coal and nuclear energy capacities are going to decrease. This is affected by green transition and energy crisis which was discussed in chapter 3.1. Energy crisis has gathered interests and attention for renewable energy, and it has been a positive boost for renewable energy's production in the future (Calthrop 2022). This opens up a lot of opportunities to P2X technology because renewable energy is then easier to access, and prices may decrease even more.

One option for P2X's energy source is its own renewable energy plant such as wind turbine. For example Bos et al. (2020) found out in their research that power to methanol's production costs are around 300 €/t which is cost-competitive to conventional methanol production, but when capital costs of wind turbine is added, the total costs of power to methanol rise to 800€/t. So initial investments such as wind turbine can be really high in P2X technologies, and this effects overall production costs a lot, but it may not achieve wanted cost advantage.

Also, renewable energy sources electricity price has been decreasing in the 2010s as we noticed in chapter 3.3. If above's capacity growth forecast will be accurate it could help to reduce renewable electricity's price even more. Solar foods (2023b) state that if renewable energy's electricity prices drop they will be cost competitive with ease.

All our P2X examples consume hydrogen, and its production is one of the main electricity consumers and also initial investments. For example, Saygin et al. (2023) announced that in their study on average 86 % of the total costs go to the production of hydrogen in power to ammonia.

Table 3 represents electrolysis efficiency development estimate in the future. As we can see from the figure, energy efficiency of electrolysis is low at the moment especially in low-temperature electrolysis, but efficiency will develop in the future.

Table 3: Development of electrolysis efficiency (Agora Verkehrswende et al. 2018)

	2020	2030	2050
Low-temperature electrolysis	67%	71%	80%
High-temperature electrolysis	81%	84%	90%

Comparable results were proposed from Gorre et al. (2019). They estimated that low-temperature water electrolysis efficiency will increase to 75-78 % in 2030. If efficiency reaches these levels it lowers P2X's electricity consumption and production costs a lot. Overall electrolyser's construction and assembling costs will reduce 25 % by 2030 (Fambri et al. 2022). Another main electricity and cost component is methanation. Also its efficiency will increase in the future to 87 % in 2030 and to 90 % in 2050 (Blanco et al. 2018).

As we have noticed in P2X process introductions in former chapter, direct air capture is one way to gain the needed CO_2. This also consumes electricity and is one the main processes. In the future also carbons dioxide's production costs with direct air capture will decrease about 40 % by 2030. (Agora Verkehrswende et al. 2018)

With green transition, emission trading system has been developed. This means that organization needs to pay for carbon dioxide emission. Also, organizations need to have permission to emissions. Emissions are measured in €/ton. This is meant to encourage organizations to reduce carbon dioxide emissions, because the less you pollute, the less you pay. (Euroopan parlamentti 2022.) In 2022 price were between 60-100 €/ton (Tiseo 2023). This is also one way that helps P2X technologies to compete against conventional technologies. For example Ikäheimo et al. (2018) found out in their research that power to ammonia becomes competitive against fossil natural gas if CO2 emission price rises to 200 €/ton

Overall P2X technologies future looks promising. Above's future aspects and reductions to P2X technologies production costs will result in better cost-competitiveness in the future against conventional production. For example, Fasihi et.al (2021) found out in their research that power to ammonia factory that generates 10 billion tons of ammonia in the best sites of world, can reach cost-competitiveness in 2030 in niche markets with total production cost of 345-420 €/ton. Best sites for power to ammonia could have rather excellent solar and wind resources such as deserts or low weighted average cost of capital (WACC) of investments such as Northwest European countries.

6 Conclusion

This study's objective was to illustrate the production costs and the share of electricity costs in chosen P2X technologies. Also cost-competitiveness against conventional technologies and future aspects were studied. Overall study was successful. Study's research questions were answered and objectives were accomplished.

Q1: How significant is the impact of electricity costs on the overall production costs of Power-to-X.

Electricity consumption and share of total costs are much higher in P2X technologies, than in conventional technologies. Electricity's share is 41-83 % of the total production costs in P2X technologies and equivalent number for conventional processes are 13-39 %. Electricity is used a lot more in P2X technologies than in conventional processes. Therefore electricity costs have a significant impact on the total production costs in P2X technologies.

Q2: How does electricity cost effect to cost-competitiveness?

Because electricity has significant impact on P2X's production costs, electricity costs effect a lot to its cost-competitiveness against conventional technologies. Only cost competitive P2X product is ammonia at the moment. Otherwise, all the products were about 2-3 times more costly to produce compared to conventional methods. P2X is not cost-competitive at the moment, because of inefficient electricity consumption and price of electricity.

Renewable energy sources will develop, and their capacity will grow in the future and renewable energy prices will continue to decrease. Because of that P2X can be cost-competitive with conventional production technologies in the future approximately in 2030. Also, society drives companies and consumers to more emission-friendly living, that will increase interest towards P2X technologies and renewable energy sources.

Since electricity has a huge role on P2X technologies, it is safe to say that the energy crisis could have had a huge impact on overall P2X development and cost-competitiveness against conventional process. Still, the energy crisis did not have any negative effects on P2X. The energy crisis increased people's interest in renewable energy sources and therefore it affected positively to P2X technologies.

Thesis results on electricity share from total costs (Q1) may not be exact, since electricity consumption and share vary on numerous things such as efficiency and electricity price. These results illustrate the electricity costs, as objective was. The results to Q2 are relatively credible, as electricity costs are a large part of production costs. The share of electricity costs was much higher in P2X production than in conventional processes, so changes in electricity costs have a much greater impact on them and thereby on cost competitiveness against alternative processes.

Since power to food does not have a lot information at the moment, it could be interesting to do further research about it, especially focusing on the process. According to this research, the future of P2X looks promising. So it could be interesting to repeat a similar study in the future focusing on the costs competitiveness, efficiency of the process and thereby the consumption of electricity, and study how these have developed in past years.

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