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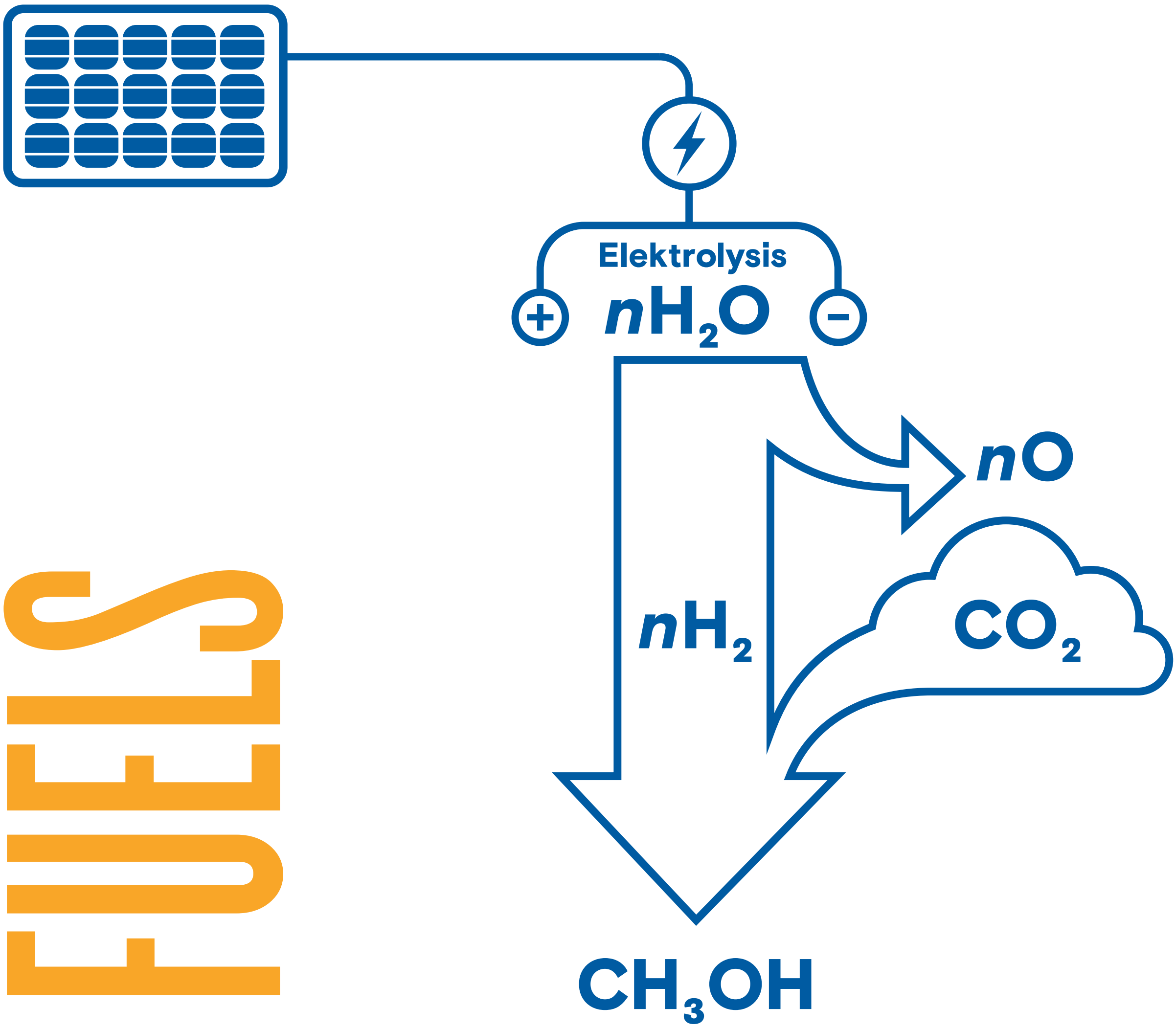

REPORT PHASE I

Setting up a Centre of Excellence for Power-to-X Technology at Adama Science and Technology University to alleviate energy poverty in rural Ethiopia

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EXECUTIVE SUMMARY

INTRODUCTION

Power-to-X or short P2X is a key technology for the decarbonization of the global economy, as required to meet the Paris Agreement (see section 1.1). It allows for the transformation of renewable electricity into all kinds of fuels and chemicals. It is a prerequisite for the decarbonization of heavy industry as well as parts of the transport sector and enables seasonal mass-scale storage of renewable electricity. Furthermore, it can also play a major role in the decarbonization of regional economies that lack a suitable infrastructure for the electrification of heavy load applications. Today, P2X is more costly than fossil fuel technology. However, due to the growing momentum for climate mitigation action, P2X is starting to enter a boom phase that will likely result in higher efficiencies and lower prices. At the same time, regulatory framework conditions that have been in favor of fossil fuels for a long time are gradually being adjusted to reflect the true costs more appropriately.

Primarily wealthy countries in Western Europe, America and Asia are starting to invest heavily in P2X technology as part of their energy transition plans. For developing countries, it is usually not feasible to do the same as they have more existential issues to resolve and very limited financial resources. However, climate change mitigation will only work on a global scale. It is the duty of wealthy countries, who are to a large part responsible for the current climate crisis, to support developing countries in their energy transition.

Ethiopia, as one of the least developed countries (LDC), is ill-prepared to perform the energy transition. Today, a large part of the population suffers from energy poverty – with grave consequences for local biomass reservoirs and the affected population. Its dynamically developing economy will result in fast growing CO_2-emissions despite its pledge to the Paris Agreement and respective big additions in renewable energy infrastructure. P2X possesses the potential to address this issue. As Ethiopia is well-endowed with renewable energy potentials, excess renewable energy potentials could be used to produce substitutes for fossil fuel products and biomass energy for the national and international market. However, Ethiopia lacks the public and political awareness, the technical capacities and the financial resources to act upon the chances presented by P2X (see section 1.2).

With the “Solar Fuels” project, the involved partner institutions want to lay the foundation for the development and implementation of P2X projects as part of the Ethiopian energy infrastructure (see section 1.3). By developing, realizing and operating a Power-to-Methanol (P2MeOH) research and demonstration plant, local researchers and students are enabled to undergo training and do applied research in P2X as well as to advocate on behalf of the technology.

The project follows an approach in 3 phases (planning, implementation and research) that span a total of 6 years. The present report summarized the results of the planning phase, where a feasibility study for the envisioned infrastructure was carried out (see section 3) and the first concepts for the research plan (see section 4) and the syllabus (see section 5) were created.

Following the planning phase, the envisioned infrastructure will be built (implementation phase) and used to conduct training and research (research phase).

PLANNING PHASE RESULTS

As a first step in the planning phase, the project team decided to take a step back and question the initial plan to build a Power-to-Methanol (P2MeOH) plant by **evaluating the different options for P2X pathways** in a multi-criteria-analysis (see section 2.1). The results confirmed the initial plan to go for methanol as the target product.

The pathway analysis was followed by the **evaluation of different variants for the Power-to-Methanol plant** including the definition of system elements and system boundaries (see section 2.2). The evaluation yielded a best variant that represents the whole P2MeOH process chain including internal photovoltaic power supply. The only exception is the production of CO_2, which will be delivered by commercial suppliers in bottles. The selection of involved system element technologies (electrolysis, gas storage, compressors, methanol synthesis and distillation) follows a state-of-the-art approach, where each element is characterized by a high technology readiness level (TRL). More experimental technologies were deemed too costly and unfit for the demonstration purpose of the plant.

As the variant selection has a large influence on the research that can be performed with the plant, **a first concept for the research plan** was elaborated in parallel to the variant evaluation. It defined a total of 7 key areas of research spanning thematic fields such as applied engineering and process optimization, applied material sciences, social sciences, ecological system design and advocacy and promotion (see section 0).

Following up the variant evaluation and definition of system boundaries and system elements, the **pre-engineering** including the sizing of main components was carried out. Herefore, several use cases for the operational strategy (i.e. whether electrolysis and methanol synthesis are run continuously or only upon availability of photovoltaic electricity) of the plant were created, simulated and evaluated. The project team decided to follow up on a concept where the electrolysis is run flexibly when photovoltaic electricity is available and the methanol synthesis is run continuously. A detailed process flow scheme can be found in section 2.3.3.

Based on the definition of the system element sizing, quotations were collected from potential suppliers in order to create a cost estimate for the implementation phase (see section 2.4). It revealed total costs of roughly 2 Mio. CHF. Due to the current geopolitical situation, supply chain disruptions and inflation, this cost estimate is associated with significant uncertainties. This is taken into account by adding a 20%-reserve for unforeseen expenses resulting in a total Budget of 2.4 Mio. CHF.

In parallel with the feasibility study for the research and demonstration plant, a research plan concept was developed. This concept foresees a total of 7 key areas of research that span several scientific disciplines (see section 3). Some of the key areas of research lie in the core competence of ASTU (e.g. the development of catalyst materials), other key areas of research will require collaboration with partner institutions (e.g. the life cycle assessment of P2X technology).

Last but not least, a first concept of how to improve the teaching of P2X disciplines and concepts at ASTU was created. It should be noted, that Dr. Dinsefa Mensur has furthermore already managed to establish a PhD curriculum in the field of P2X at ASTU in parallel to the planning phase.

Table of Content

Abbreviations

AEL	Alkaline electrolysis
AEM	Anion exchange membrane
ASTU	Adama Science and Technology University
CAPEX	Capital expenditures
CO	Carbon monoxide
CO_2	Carbon dioxide
CO2e	Carbon dioxide equivalents
CCU	Carbon capture and utilization
CCS	Carbon capture and storage
CCS	Ethiopian statistics service
DAC	Direct air capture
DME	Dimethyl ether
FT	Fischer-Tropsch
GDP	Gross domestic product
IET OST	Institute for Energy Technology of University for Applied Sciences of Eastern Switzerland
IRENA	International renewable energy agency
LDC	Least developed countries
MtCO2e	Million tons of CO_2 equivalents
NDC	Nationally Determined Contributions
OPEX	Operational expenditures
P2H2	Power-to-Hydrogen
P2CH4	Power-to-Methane
P2MeOH	Power-to-Methanol
P2DME	Power-to-Dimethyl ether
P2NH3	Power-to-Ammonia
P2FT	Power-to-Fischer-Tropsch
P2X	Power-to-X
PCI	Per capita income
PEMEL	Proton exchange membrane
PV	Photovoltaics
SOEC	Solid oxide electrolysis
TES	Total energy supply
TRL	Technology readiness level

1. INTRODUCTION

1.1 POWER-TO-X

1.1.1 What is Power-to-X and why is it relevant?

Power-to-X (P2X) is the sum term for the storage of electrical energy ("Power") in a variety of products ("X") (see Figure 1). The main P2X technologies are often categorized according to whether the product appears as a gas (power-to-gas P2G) or a liquid (power-to-liquids P2L) at room temperature. Sometimes, the definition of "X" is also stretched beyond chemicals to concepts like heat and mobility (Power-to-heat and Power-to-Mobility).

Most P2X products can serve as fuel. Due to the production processes involved they are often referred to as "efuels" or "synfuels" and the process is also summed up under the term Power-to-Fuels.

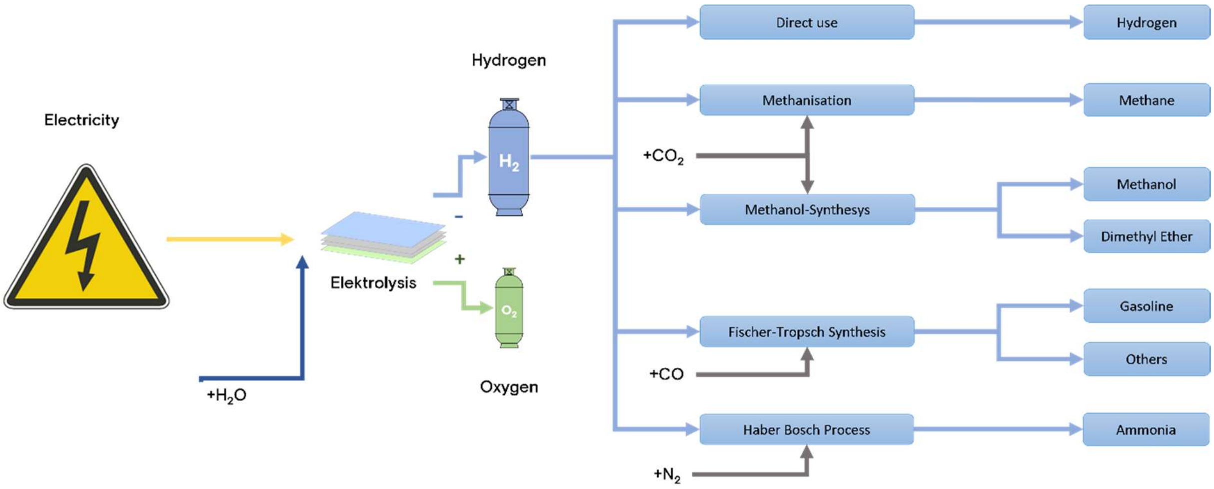

Figure 1 Power-to-X: Conversion of electricity into various forms of chemical energy carriers.

P2X is regarded as a key technology for the global energy transition. In distinction to other electricity storage technologies such as batteries and pumped-storage, P2X allows for the flexible storage of renewable electricity at a much larger scale (see Figure 2).
Synfuels can be stored, transported and used just like their fossil equivalents. Therefore, they can replace fossil fuels wherever their characteristics are indispensable (e.g. jet fuels, long-distance transport vehicles, backup generators, chemical feedstock), better alternatives are unavailable (e.g. in places with no access to grid electricity) or act as seasonal energy storage (e.g. to shift energy surpluses from the summer to winter time mid to high latitudes).

On top of that, system integration of P2X plants can also provide services to the local and regional electricity grid through flexible operation. In times of oversupply, P2X plants can store excess electricity that would otherwise be wasted. When electricity supply falls short, P2X plants can pause their operation or even deliver electricity back to the grid [1].

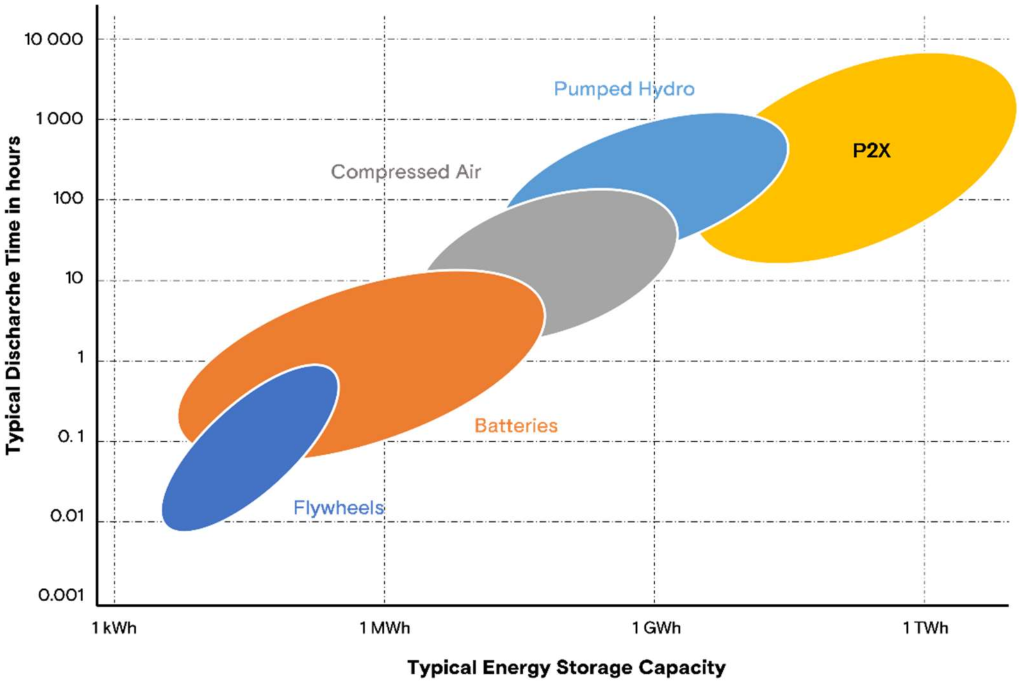

Figure 2 Storage capacities and discharge times of different energy storage systems, Source [3]

P2X can furthermore play a vital role in the decarbonization of industry, by providing free or low greenhouse gas emission chemicals. Examples are green hydrogen for steel and other high-energy intensity manufacturing, green ammonia for fertilizer production and green methanol for plastics manufacturing.

The World Energy Council Germany estimates, that the global demand for synthetic fuels required for global decarbonization by 2050 lies somewhere between 5 and 20 percent of today's global annual primary energy consumption [3].

1.1.2 P2X Products and Working Principles

The main system element of every P2X technology is the electrolysis of water. The produced hydrogen can be used directly as a chemical feedstock and energy carrier (section 1.1.2.1), or to produce a number of hydrogen derivatives such as methane (section 1.1.2.2), methanol (section 1.1.2.3), dimethyl ether (DME) (section 1.1.2.4), gasoline or kerosene (section 1.1.2.5) or ammonia (section 0).

Depending on the desired product, additional inputs are required (see section 1.1.3.2). In most cases, the required input is carbon in the form of carbon dioxide (CO_2) or carbon monoxide (CO). In the case of ammonia, the required additional input is nitrogen gas.

An overview of different P2X technologies is given in the following chapters.

1.1.2.1 Power-to-Hydrogen P2H2

P2H2 is the simplest type of P2X technology. In P2H2, the hydrogen is used directly without further processing. P2H2 is often times simply referred to as hydrogen technology. Given that hydrogen is produced from renewable electricity, it is labeled as “green” hydrogen. However, there is a number of ways to produce hydrogen from all kinds of fuels or electricity (see Figure 3). Most commonly, hydrogen is produced through steam reforming of fossil fuels (“grey” hydrogen).

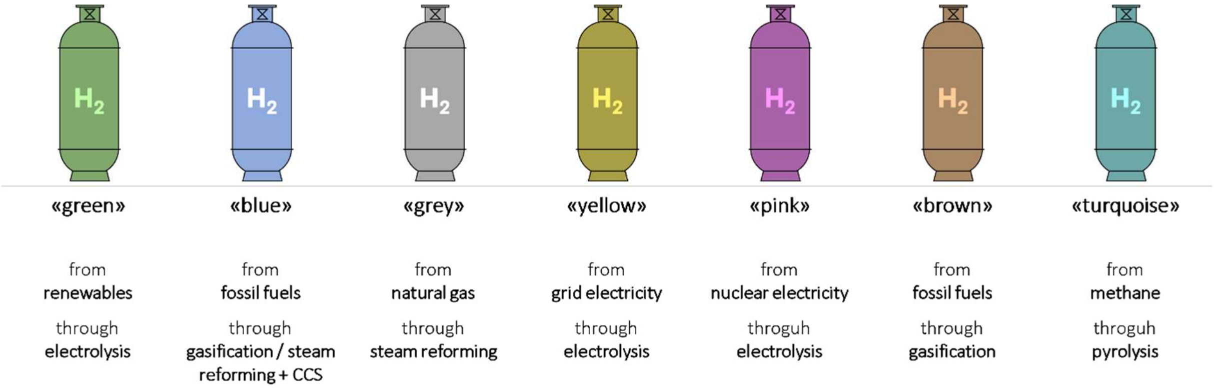

Figure 3 hydrogen color code, based on [3]

In addition to the hydrogen production processes highlighted in Figure 3, hydrogen can also be obtained through photoelectrochemical splitting of water, bioelectrochemical splitting of water and thermochemical splitting of water. Whilst the latter is already at the threshold of large-scale piloting (e.g. through the Swiss ETH-spinoff Synhelion, **HTTPS://SYNHELION.COM/**), both the photoelectrochemical and bioelectrochemical (i.e. using the same processes as photosynthesis) splitting of water are still investigated in the lab scale.

The core piece of P2H2 is the electrolyser unit. It uses water and electricity as the main inputs to produce hydrogen and oxygen (see Figure 4). Up to date, there are three types of electrolysers that are commercially available on a large scale:

- Alkaline electrolysers (*AEL)*
- Proton Exchange Membrane electrolysers (*PEMEL*)
- Solid Oxide electrolysers (*SOEC*)

While *AEL* technology has been around for many decades, *PEMEL* only recently made it to the commercial scale and is still in the process of upscaling. The same is true for SOEC electrolysers, however, their technological maturity is lower and it faces challenges with regard to durability. In addition to the three available types on a commercial scale, there are several other types and sub-types under development. The international renewable energy agency IRENA highlights the anion exchange membrane (*AEM*) electrolysers as an additional promising concept. Amongst all type of electrolysers, solid oxide electrolysers (*SOEC*) are regarded to have a particularly high potential in terms of conversion efficiency. The main advantage of *PEM* electrolysers is their high conversion efficiency in combination with the highest flexibility to deal with fluctuating loads – a characteristic that is particularly interesting in combination with intermittent renewable energy sources like solar, and, to a lesser degree, wind. A good introduction to electrolysis technology is given by IRENA [4].

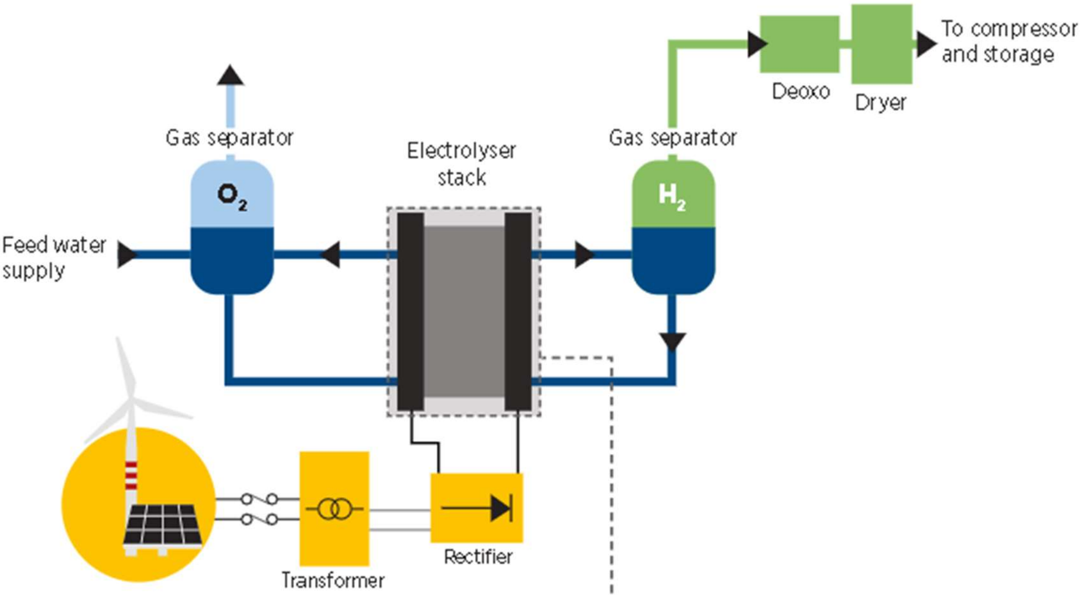

Figure 4 Basic components of P2H2 at the system level, Source [4]

Due to its simplicity, P2H2 has the highest conversion efficiency of all P2X technologies. It is assumed that P2H2 efficiency can reach up to 90% or even more in the long term thanks to the growing maturity of *SOEC* technology [5]. A record efficiency of 84% for its EU-funded *GrInHy2.0 hydrogen* project with a high-temperature SOEC electrolyser from the Dresden-based company Sunfire has been reported by the German steel manufacturer Salzgitter AG in 2022 [5]. However, using the more established *AEL* and *PEMEL* technologies, conversion efficiencies of around 60% to 70% are more realistic today [5]. A key driver for elevating the conversion efficiency is heat management by coupling electrolysis with other heat providing or demanding applications.

The main drawback of P2H2 is related to the specific characteristics of hydrogen as a volatile gas with a very low volumetric energy density and a very small molecular size[1]. In order to overcome these drawbacks, hydrogen needs to be stored and transported at high pressure or in a liquified state. Both are energy intense and consequently diminishes the advantage of high conversion efficiency. In addition to this, hydrogen needs to be handled with care due to its reactivity with oxygen.

1.1.2.2 Power-to-Methane P2CH4

In P2CH4, hydrogen is further processed to methane using either the catalytic or thermochemical methanation or the biological methanation [7] (see Figure 5). Methane is the main component of natural gas and globally in widespread use.

In the catalytic or thermochemical methanation, hydrogen and CO_2 are reacted to methane at a temperature of 150 to 500°C and a pressure of up to 100 bars in the presence of metal catalysts. There is a wide range of technological concepts for the catalytic or thermochemical methanation ranging from the well-established Sabatier process to research state processes like the in-situ methanation in SOEC electrolysers [8].

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[1] The size of a hydrogen molecule is in fact so small, that it tends to gradually diffuse out of every container, especially when stored under high pressure.

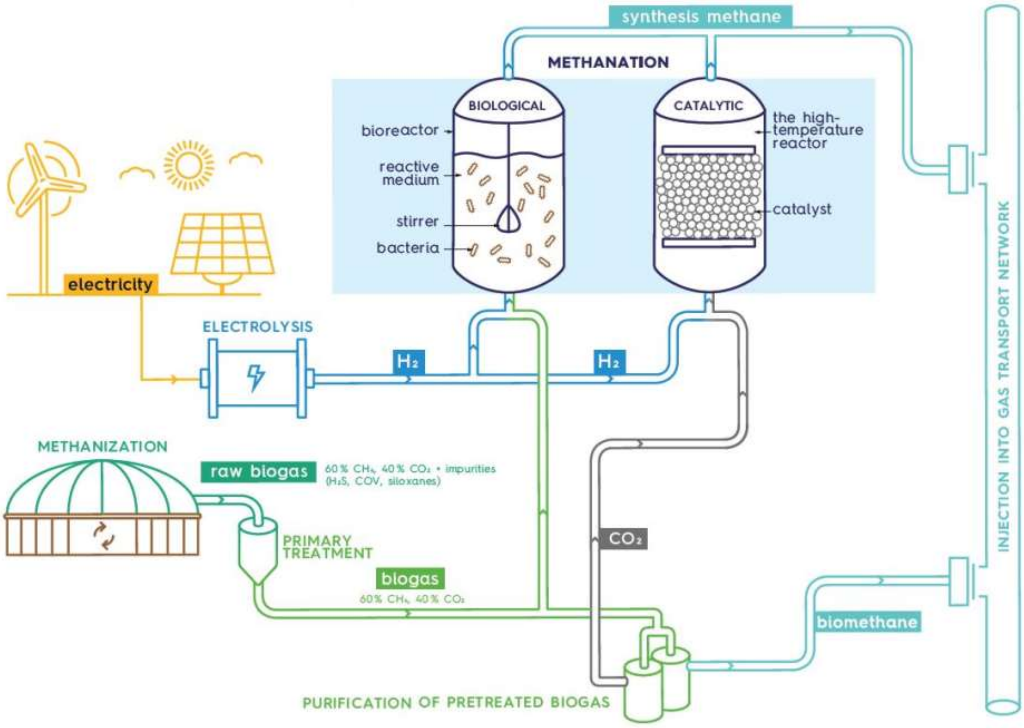

Figure 5 Illustration of the two main methanisation routes. Source: [9]

In the biological methanation, hydrogen and CO_2 are reacted to methane in absence of oxygen through methanogenic archeans. The biological methanation can either take place in specifically designed reactors that use biogas and hydrogen as a feedstock as it has been implemented at the Swiss utility company *Limeco* site in Dietikon [10], or in geological repositories as it has been demonstrated by the international joint research project *Underground Sun.Conversion* in Austria [11].

The efficiency of the methanation process is reported to be somewhere in the range of 60% [12] to 85% [7]. These additional conversion losses need to be justified by an increased value of methane in comparison with hydrogen. This additional value is arguably given by the fact that methane has a higher volumetric energy density and is fully compatible with existing natural gas infrastructure present in many cities and countries (i.e. distribution networks and storage systems). Because of this, P2CH4 is considered a good energy storage alternative for time-shift applications of renewable energy sources.

In order for the produced methane to be rated as renewable, the CO_2 is required to be either captured from air (direct air capture DAC), seawater, or stem from biogenic sources such as organic waste. If the CO_2 is captured from waste gas of fossil fuel combustion or fossil fuels based cement production, it cannot be deemed renewable, since the CO_2 will eventually still end up in the atmosphere (for a more detailed discussion of carbon sources for P2X see section 121.1.3.2). The different options for CO_2 sourcing may explain the large difference in the conversion efficiencies reported for the methanation process.

1.1.2.3 Power-to-Methanol P2MeOH

Methanol is a basic chemical compound required as a feedstock for a variety of other chemicals such as formaldehyde and numerous plastics. Apart from that, it can also be used as versatile fuel in combustion engines or methanol fuel cells. Furthermore, many countries blend their gasoline with 5 to 15 % of methanol. Its steadily growing global annual production is currently about 100 million tons and methanol production makes up about 10% of the CO_2 emissions of global chemical industry. Today, Methanol is almost exclusively produced from fossil fuels. Renewable methanol can be produced either from biomass (bio-methanol) or from hydrogen and CO_2. An overview of methanol production routes is given in Figure 6. [6]

The core element of P2MeOH is the catalytic methanol synthesis. There are a variety of commercially available concepts for methanol synthesis using a range of temperatures (200°C – 300°C), pressures (30 – 100 bar) and catalyst mixtures (usually based on $CuO/ZnO/Al_2O_3$). Some of them have been in uses for many decades, others are still under development. In any case, P2MeOH requires a carbon source in addition to the hydrogen as feedstock, just like P2CH4. The carbon source can either be CO_2, syngas (a mixture of hydrogen, CO and CO_2) or methane. If syngas is used as a carbon source, sulfur and chloride compounds need to be scrubbed from the syngas in order to prevent fast catalyst poisoning.

Similar to the methanation process, the conversion efficiency of the present methanol synthesis technology is reported to be up to 80%. Thus, the overall efficiency of P2MeOH lies between 40 and 65% today and may increase substantially to up to near 80% in the future with increasing technological maturity of electrolysis and methanol synthesis technology as well as optimized heat management. Even though the methanol synthesis is a well understood technology, commercial experiences are mostly limited to the continuous operation based on fossil fuels and syngas. Research on the flexibility and dynamic operation as it is required for green P2MeOH technology is still very limited.

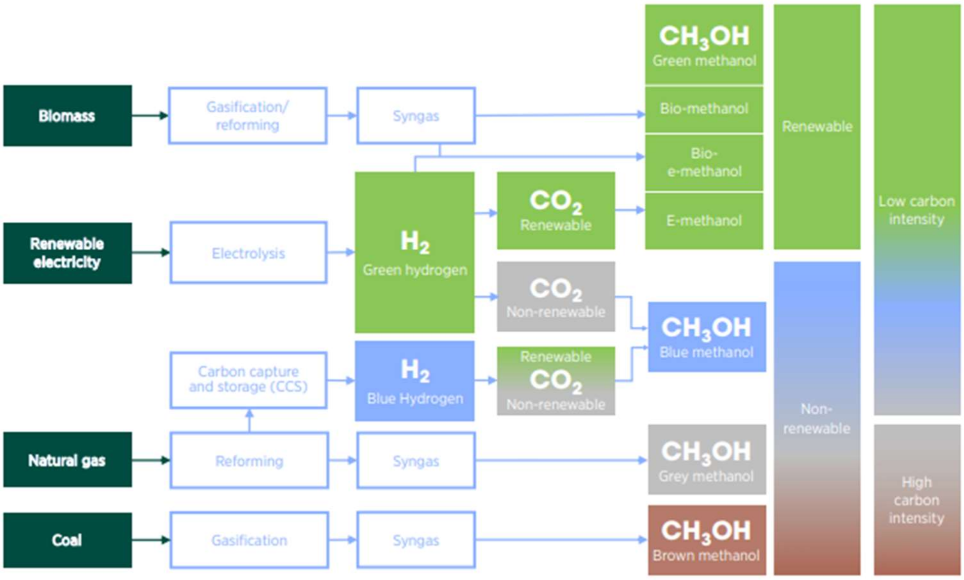

Figure 6 Principal methanol production routes. Source: [6]

Since methanol is liquid at atmospheric conditions, it is easy to handle and store. Additionally, the combustion of methanol is very clean (the combustion of methanol yields nothing but CO_2 and water vapor), which makes it particularly interesting as a fuel in places where people are exposed to exhaust gases. However, there are also some drawbacks. Methanol is flammable and toxic when ingested. Thus, it too needs to be handled with care. Furthermore, its volumetric energy density is only about half as large as the one of gasoline and diesel fuels.

1.1.2.4 Power-to-DME P2DME

Dimethyl ether is a highly flammable, relatively non-toxic chemical that serves as a basic feedstock in the chemical industry, as a refrigerant and as a fuel and in a number of niche applications. Similar to methanol, DME can be used to blend fuels, or, with slight modifications of the engines, used as a fuel directly. At ambient conditions, DME is gaseous (boiling point –24.8 °C).

Today, DME is almost exclusively produced from methanol through dehydrogenation. However, DME can also be produced from syngas directly by in-situ combination of methanol synthesis and dehydrogenation that brings about some advantages in the equilibrium of the methanol synthesis reaction. In contrast to the route via methanol, experiences with the direct DME production route are still relatively scarce. The required temperature and pressure conditions for direct DME production from syngas are similar to the ones for methanol synthesis, but it requires additional catalysts. The conversion efficiency of P2DME is a bit lower but similar to the one of P2MeOH.

1.1.2.5 Power-to-Fischer-Tropsch Synthesis P2FT

Fischer-Tropsch (FT) synthesis is a well-established process for the conversion of syngas into short to long chain fuels such as gasoline, diesel and wax. Whereas the experience with the process based on syngas produced from natural gas, coal and biomass is quite extensive, direct utilisation of CO_2 has not been investigated excessively on a larger scale. Due to the limited experiences with CO_2-based feed gases for FT-synthesis and the early stage of FT catalyst development for direct CO_2 conversion, planned and realised P2FT plants exclusively rely on a shift from CO_2 to CO via RWGS-reactor (Reverse-Water-Gas-Shift) or co-electrolysis. Generally, syngas with a H_2/CO ratio of 2–2.2 is processed on an iron or cobalt catalyst at temperatures of at least 160–200 °C at ambient pressure. Depending on the carbon chain growth probability, only a small product fraction can directly be used as a diesel fuel. The product of FT-synthesis has to be fractionated to gain valuable products. Waxes have to be treated further by hydrocracking to be converted into fuels. [14]

1.1.2.6 Power-to-Ammonia P2NH3

With a global annual production of more than 175 million tons, ammonia is a key chemical supporting modern civilization. Ammonia production accounts for about 1% of global carbon dioxide emissions. A large part of the production is consumed by the fertilizer industry. Other important fields of application are explosives for mining, intermediary products for the pharmaceutical industry, cleaning agents and refrigerants. Recently, ammonia also gained attention for its potential as a carbon free fuel or hydrogen carrier, since it is much less energy intense to store and transport in comparison to hydrogen[2]. [8]

Ammonia is almost exclusively produced in the Haber-Bosch process, where hydrogen and nitrogen gas are reacted to ammonia under high pressure (>100 bar) and temperature (400-500°C) conditions in the presence of a metal, typically iron, catalyst. In P2NH3, the required hydrogen is obtained from water electrolysis instead of steam reforming of fossil fuels as it is done today. The nitrogen feedstock required for the process is obtained by gas separation using air.
Recently, alternative electrochemical P2NH3 concepts to the Haber-Bosch route are being developed that require much lower pressure and temperature levels. They can either use hydrogen as a feedstock or also combine the electrolysis of water with the synthesis of Ammonia in a single step. However, such concepts are still at the early stage of development. [8]

1.1.3 Current status of P2X technologies

The emergence of P2X technologies is tightly connected to the evident and increasingly urgent need for global energy transition away from fossil fuels towards a renewable, greenhouse gas emission free economy. Almost all countries have pledged to either fully or partially decarbonize their economy by 2050, which is necessary to contain the climate change to 1.5°C in comparison to pre-industrial times. This has led to energy policy changes and roadmap preparation in countries around the world (see Figure 7).

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[2] ammonia liquifies at -33°C in comparison to hydrogen that only liquifies at -253°C

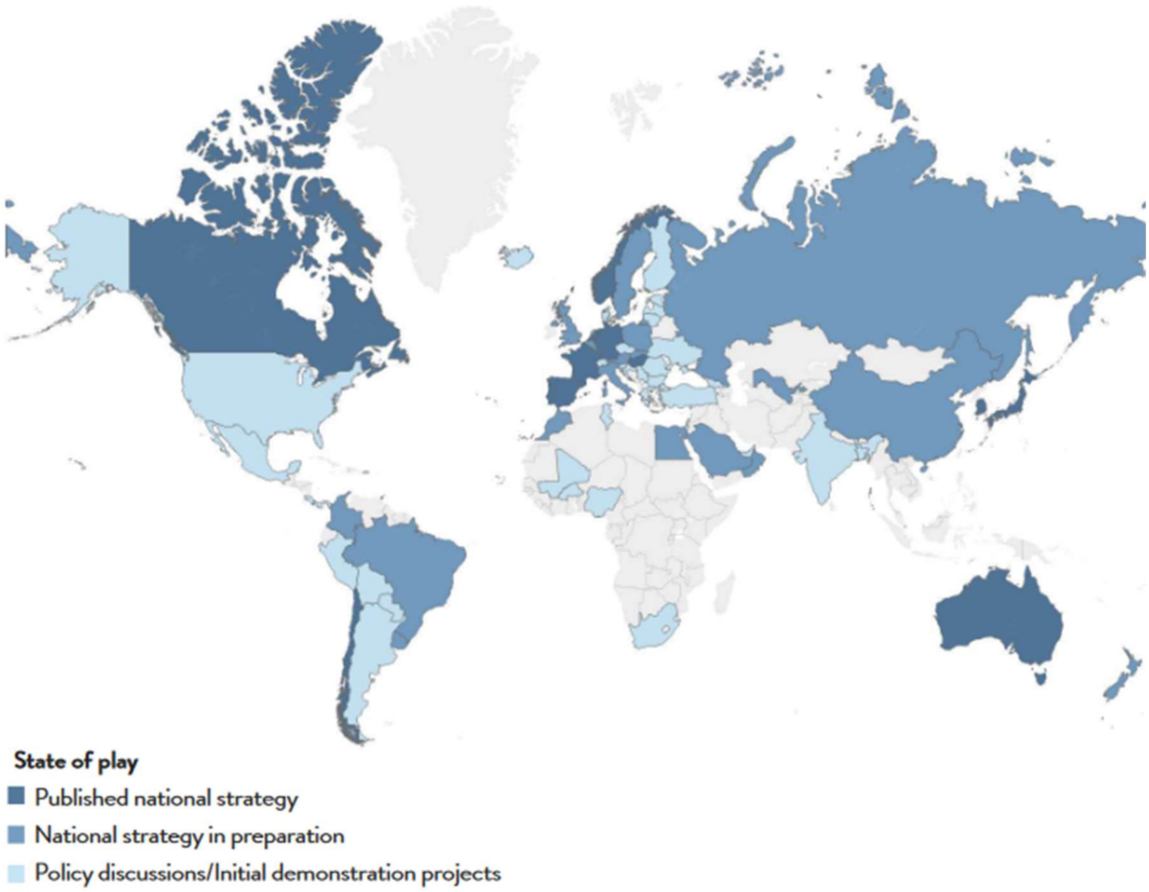


Figure 7 Overview map of the countries activities towards developing a hydrogen strategy [16]

P2X technologies are given due attention in Europe, America, parts of Asia and Arab republic countries. In Europe, about 220 P2X-related research, pilot, and demonstration projects have been implemented, completed, and planned by June 2020. These projects are driving up the cumulatively installed capacity of electrolysers from a few dozens of MW by 2020 to a few GW in the next couple of years. [17]

As has been highlighted in the previous sections, most of technologies involved in P2X at least have one subvariant with a high technology readiness level (TRL) (AEL, methanation, methanol synthesis, methanol dehydrogenation, Haber-Bosch process, Fischer-Tropsch synthesis, etc.). However, significant progress can be expected in novel electrolysis technology (SOEC, AEM and other), the upscaling of present electrolysis technology (especially PEM and SOEC), and in novel, alternative concepts for all the established technologies mentioned before (e.g. the in-situ methanol synthesis in combination with electrolysis or the Underground Sun Conversion of hydrogen and CO_2 to methane). Apart from that, there are specific challenges related to the intermittency of renewable energy as a basic feedstock for P2X and the system integration of P2X in general that are only being addressed recently.

1.1.3.1 Cost of P2X technologies today and in the future

P2X technologies generally are not cost-competitive with fossil fuel technologies today [4]. In order for this to change, fossil fuels need to become more expensive and P2X technology needs to become less expensive.

Fossil fuels are cheap for many reasons. One important reason is the scale of production. Another reason is that their prices do not reflect their true costs. On the one hand, externalities from fossil fuel use (climate change effects, local air pollution effects) are mostly not or only partially reflected in the prices. On the other hand, low energy costs are a desired product of government subsidies as they keep the economy running smoothly through the provision of jobs and inexpensive fuels for industry and consumers. The drastic effects of fast increasing fossil fuel prices and their impact on inflation can be observed currently in the wake of the war in Ukraine.
The cost of P2X technology is largely dominated by the costs for renewable energy, the annual operation time of electrolysers and the investment costs for P2X infrastructure, especially the electrolysers [18].

Only recently, renewable electricity became cost competitive with conventional power plants and in an increasing number of places, the levelized cost of solar PV and wind electricity is now lower than the one of conventional power plants (see Figure 8). It can be assumed, that renewable energy electricity prices will continue to decrease in the future [18].

For P2X to be commercially viable, inexpensive electricity prices are an imperative. Renewable electricity will likely be available at marginal or even negative prices in the future at times of renewable energy surplus. However, renewable electricity will not be available at marginal prices all the time (otherwise, nobody would invest). Furthermore, it would be a waste to keep electrolyser running during times of electricity deficits. Consequently, the operation time of P2X electrolysers will likely be limited to roughly 25 – 50% of the time. The limited operation time has large consequences for the production cost of P2X fuels, as it is nicely shown by Kober, et al. [1] and is displayed in Figure 9.

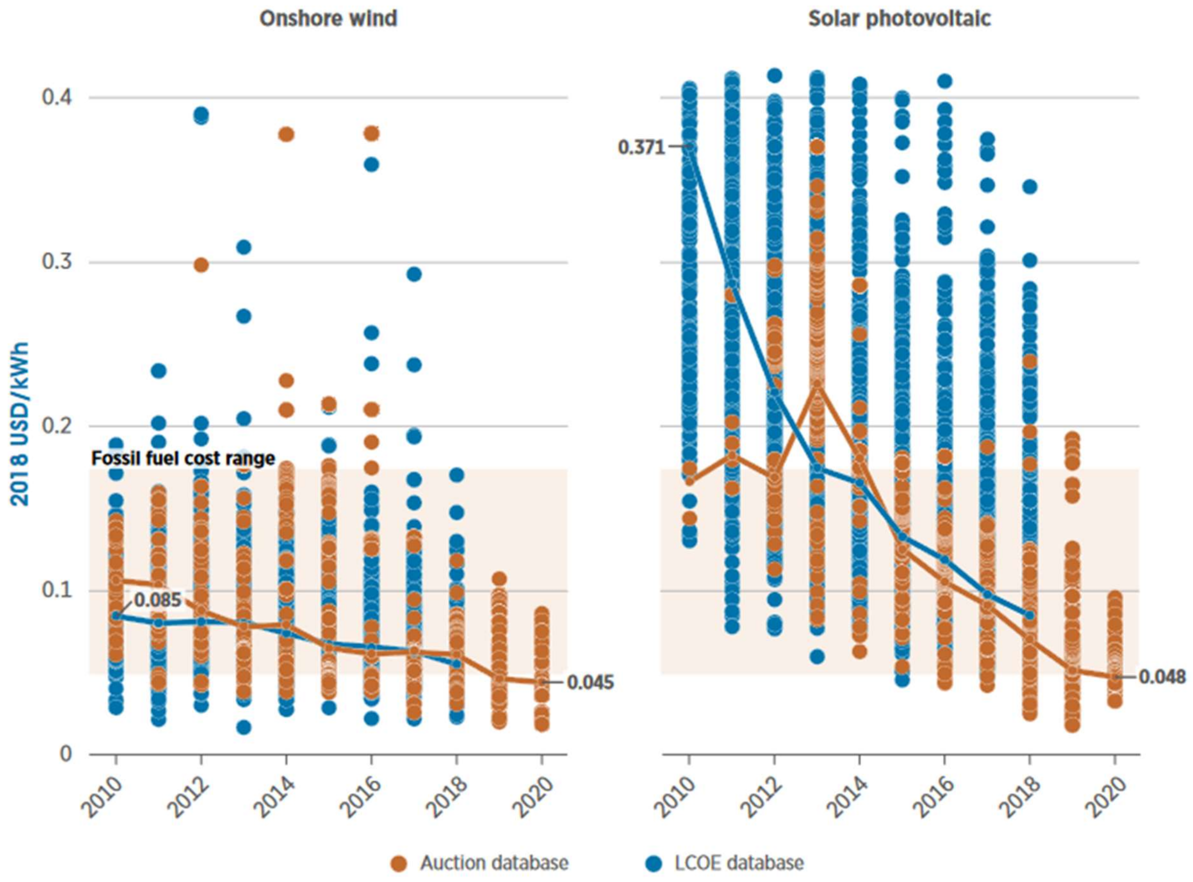


Figure 8 Global cost trends for onshore wind and solar PV. Source: [8]

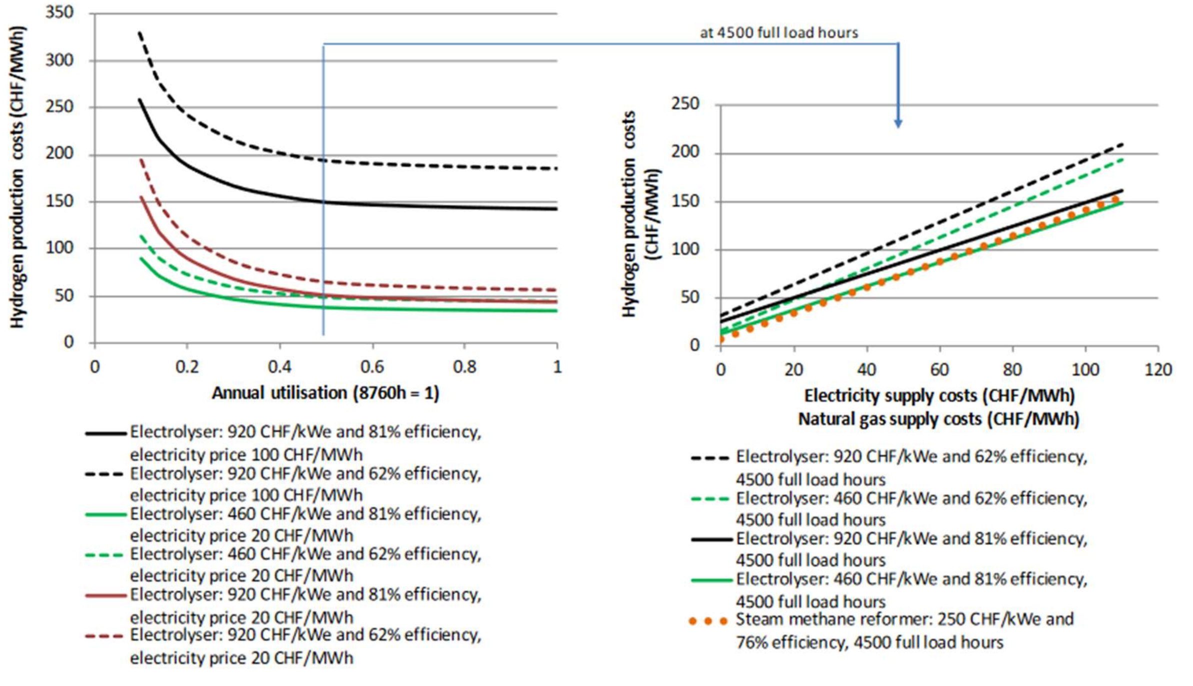


Figure 9 Hydrogen production costs for different electrolyser configurations (regarding investment costs, efficiency) as function of the annual electrolyser capacity utilization (left panel) and as function of the costs for electricity supply (right panel). For comparison the right panel includes hydrogen production costs for steam methane reforming, which are depicted relative the costs for natural gas supply. For all hydrogen production technologies maximum 90000 total operation hours or 20 years lifetime and a discount rate of 5% is assumed. Source: [1]

The specific investment costs of P2X infrastructure depends largely on the economies of scale. However, investment costs for electrolysers are still very high due to the low production scale. It is assumed that electrolyser costs will come down from roughly 500 – 2’000 USD per kW today to as little as 100 – 200 USD per kW by 2050 thanks to market growth and improved technology. [20]

Overall, IRENA [4] estimates that a price decrease for green hydrogen from today roughly 5 USD per kg hydrogen to 1 USD per kg hydrogen can be achieved, mainly through the abovementioned improvements (see Figure 10).

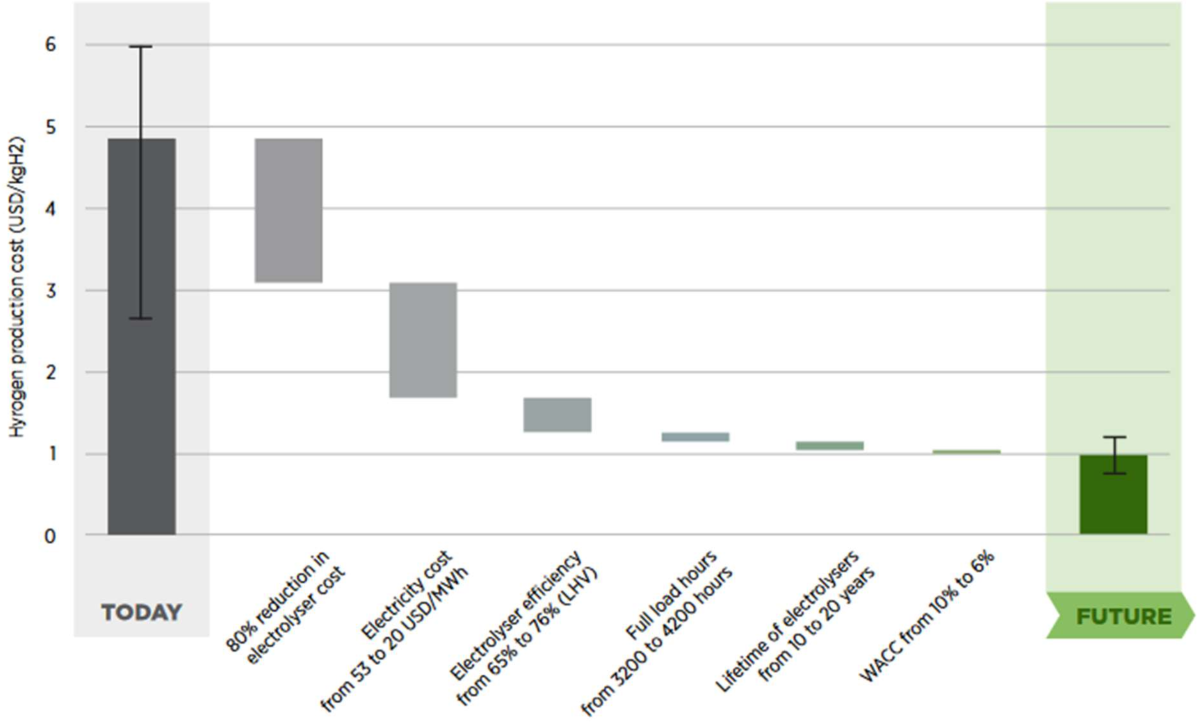


Figure 10 Step changes for achieving green hydrogen competitiveness. Source: [4]

1.1.3.2 How to obtain the carbon feedstock for P2X technology

Most of the P2X technologies (exceptions are P2NH3 and P2H2) require carbon as a feedstock; either as carbon dioxide CO_2 or carbon monoxide CO.
The carbon feedstock can be obtained from a number of sources:

- Post combustion capture from power plants
- Pre-combustion capture from power plants
- Capture from industrial processes (such as the calcination process in a cement plant and the production of sodium phosphate)
- Direct air capture (DAC) from ambient air
- Carbon capture from ocean water
- Fermentation of biomass

Whenever the carbon feedstock is derived from fossil fuels, its use for the production of a P2X product cannot be considered carbon neutral. In effect, the emission of CO_2 is simply shifted from the plant where it is captured to the place where the P2X product is used. This concept is known as carbon capture and utilization CCU. With regards to climate change mitigation, it would be much more desirable to store the captured carbon instead of utilizing it (carbon capture and storage CCS), so that it cannot act as a greenhouse gas.

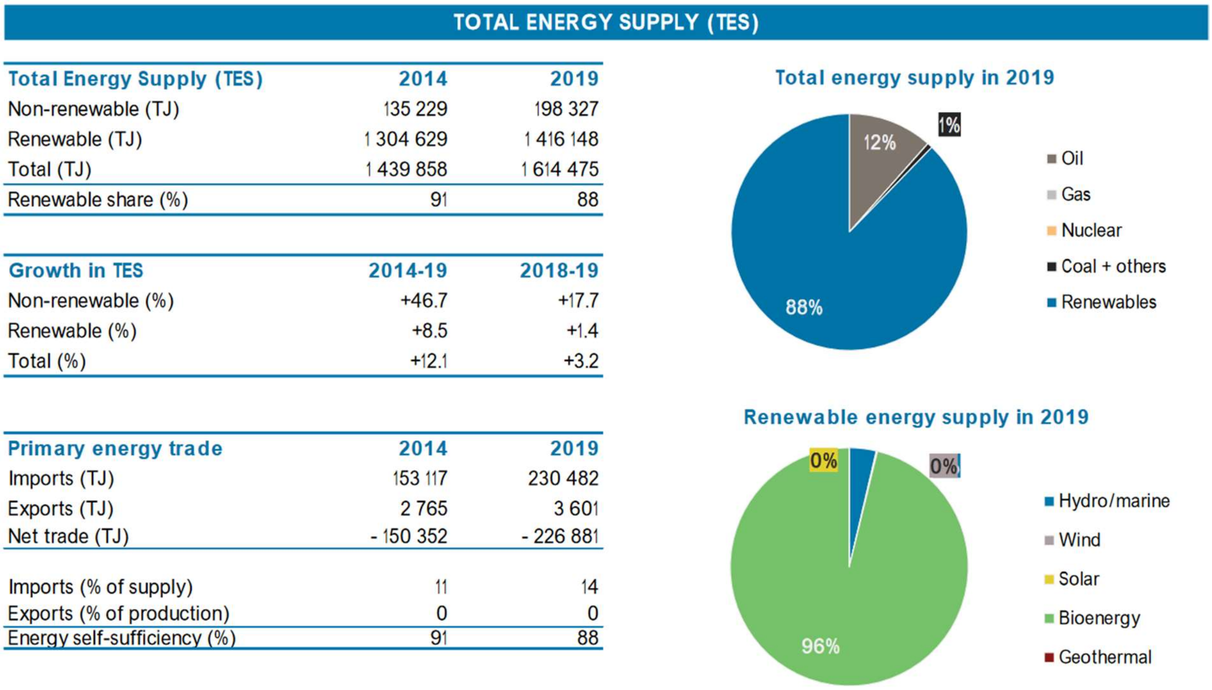
If the carbon feedstock is derived from a renewable source (i. e. biomass such as wood and agricultural waste), it can be considered renewable. However, the precondition is that the respective biomass reservoir (e.g. a forest) is managed sustainably.
Direct air capture DAC or ocean capture is fundamentally different. These technologies remove CO_2 from the two reservoirs where it either directly (the atmosphere) or indirectly (the ocean, through the exchange of CO_2 with the atmosphere) acts as a greenhouse gas. Its removal results in negative CO_2 emissions and the subsequent use as a feedstock for P2X will result in a neutral carbon balance.

A broad variety of processes have been developed in order to separate CO_2 from the abovementioned sources. They mostly rely on adsorption, absorption, membrane separation or the direct utilization in P2X plants. Which process is suitable depends largely on the actual source and the given framework conditions. Carbon capture technology is also assumed to significantly reduce its costs thanks to larger scale production.

1.2 ENERGY IN ETHIOPIA

1.2.1 Situation Today

Ethiopia’s total energy supply (TES) today is characterized by a low primary energy demand of roughly 1 MWh per capita and year [21] (for comparison: The Swiss primary energy consumption is roughly 30 times bigger) that is mostly derived from biomass (see Figure 11). The few fossil fuel resources that are consumed in the country are imported and mainly linked to the transportation sector. Ethiopia is a typical example for the prevailing energy poverty in sub-Sahara Africa.



TOTAL ENERGY SUPPLY (TES)

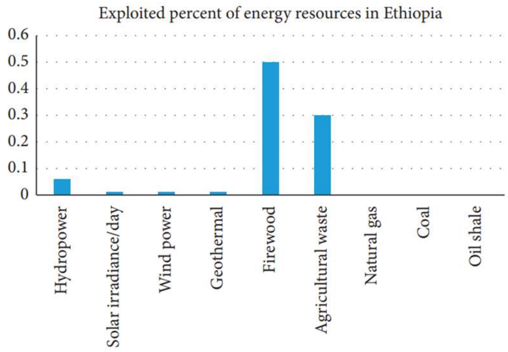
Total Energy Supply (TES)	2014	2019
Non-renewable (TJ)	135 229	198 327
Renewable (TJ)	1 304 629	1 416 148
Total (TJ)	1 439 858	1 614 475
Renewable share (%)	91	88

Growth in TES	2014-19	2018-19
Non-renewable (%)	+46.7	+17.7
Renewable (%)	+8.5	+1.4
Total (%)	+12.1	+3.2

Primary energy trade	2014	2019
Imports (TJ)	153 117	230 482
Exports (TJ)	2 765	3 601
Net trade (TJ)	- 150 352	- 226 881
Imports (% of supply)	11	14
Exports (% of production)	0	0
Energy self-sufficiency (%)	91	88

Figure 11 Total Energy Supply of Ethiopia in 2019. Source: [22]

At the same time, Ethiopia is well-endowed with renewable and non-renewable energy resources (see Figure 12). Whilst the non-renewable energy resources have not yet been exploited at all today, Ethiopia has started to exploit the renewable energy resources to meet the fast-growing demand for electricity (almost exclusively hydropower and some wind and solar). Thanks to the National Electrification Program NEP and other initiatives, electricity access has increased from roughly 5 % in 2000 to roughly 45% in 2018 [21]. However, there is a large disparity between the urban and (the much larger) rural population. While only 39.4% of rural residents have access to electricity, the number is much higher for the urban population with 93.2% by 2020 [24].



Resource	Exploitable reserve	Exploited percent (%)
Hydropower	45000 MW	0.06
Solar irradiance	4–6 kWh/m^2/day	0.01
Wind: power	100 GW	0.01
Geothermal	<10,000 MW	0.01
Firewood	1120 million tons	50
Agricultural waste	15–20 million tons	30
Natural gas	113 billion cubic meters	0
Coal	300 million tons	0
Oil shale	253 million tons	0

Figure 12 Energy resource potential and percentage of its potential usage in Ethiopia (Getie, 2020)

Ethiopia is one of the countries with the highest solar photovoltaic potentials (see Figure 13). Furthermore, the seasonality of PV production is very low thanks to the vicinity to the equator. For P2X this is especially relevant since the annual load of the electrolysis is one of the most relevant cost factors (see 2.3.1).

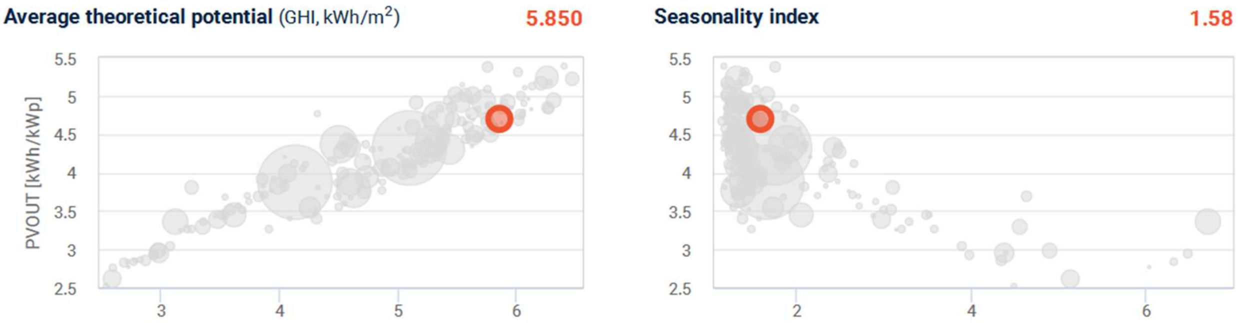


Figure 13 Average theoretical PV power potential and seasonality index of PV in Ethiopia compared to other countries. (ESMAP, 2020)

Today, most of the rural population suffers from energy poverty. Biomass, such as firewood and agricultural residues, is the only available cooking fuel for more than 90% of the population [21]. This excessive use of biomass leads to a steady decrease in biomass resources, disappearance of natural forests and biodiversity, high CO_2 emissions, and drastic consequences for society, economy, and ecology.

Furthermore, the fast-expanding electricity grid suffers from frequent power outages, as the electricity distribution network is often times not capable to maintain the balance of supply and demand. This fact can be illustrated well by looking into World Bank data on the number of expected monthly power outages (9) as well as the fraction of companies expecting power outages (80%) [23].

Energy prices in Ethiopia have been kept at highly subsidized rates distinctly lower than actual market prices. While this has a positive effect on energy access in the short term, it also leads to a lack of service quality as well as accessibility and fails to incentivize the private sector to co-invest in the Ethiopian energy sector alongside with the government. In order to overcome this situation, Ethiopia has decided to both progressively reduce government subsidies for electricity and to eliminate subsidies for fossil fuels (see Figure 14). Thus, it can be expected that energy prices in Ethiopia will be oriented towards international market prices in the future.

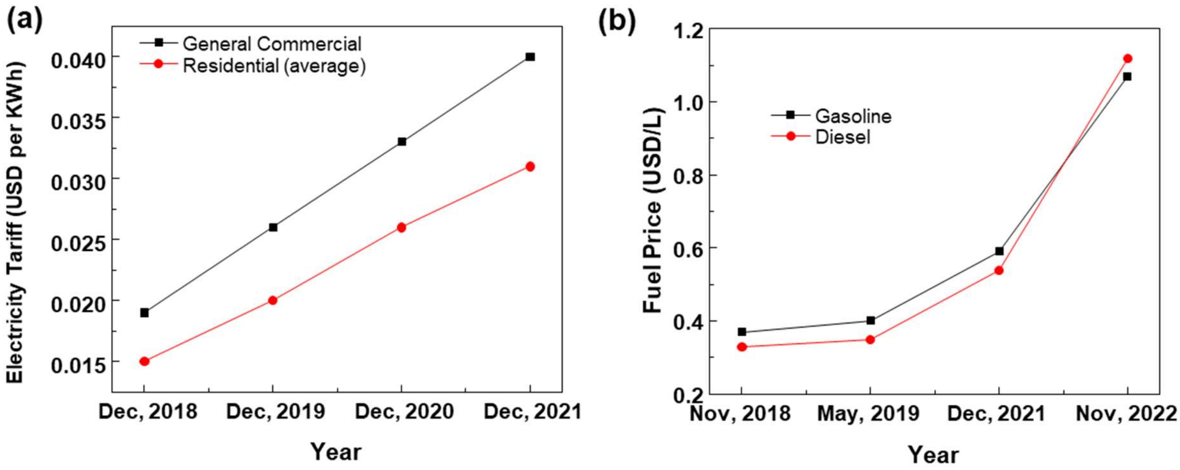


Figure 14 Electricity tariffs and fuel prices in Ethiopia during the past 4 years. Source: [27] and [28]

1.2.2 Outlook

Main drivers for energy demand

Energy demand in Ethiopia is forecasted to grow strongly in the upcoming decades. The main drivers for the development of the Ethiopian energy demand are:

- Population Growth
- Economic Growth
- Adaptions in the national energy policy framework

Quite obviously, **population growth** is one of the main drivers of energy consumption [24]. Generally, it is true, that more people consume more energy. In a situation, where the per capita energy consumption is constant, energy demand develops linearly with the population. The Ethiopian population has developed rapidly over the past decades (see Figure 155) and is expected to continue to do so in the foreseeable future.

However, the per capita energy consumption hardly remains constant in a dynamically developing country where people transition from being subsistence farmers to taking part in the modern economy with its high degree of division of labour. Probably the most relevant key indicator for **economic growth** is the gross domestic product (GDP), and, in relation to the population, the per capita income (PCI). According to the World Bank, Ethiopia's GDP has been growing with an impressive rate of 8.7% per year for the past two decades (see Figure 166 and Figure 177). At the same time, the PCI grew at a slightly lower rate, indicating that the achieved economic growth was largely due to an increase in productivity and not due to the population increase. In the same time span, the annual per capita energy consumption in Ethiopia quadrupled from 250 kWh to roughly 1'000 kWh [23].
It can be expected that the Ethiopian economy will continue to grow at a high rate in the future, even though the Covid crisis, the current inflation crisis and the Tigray war will likely leave a mark on the growth curve. A first indication for this can be found in the recent national labor force survey, which found a drastic decline in employment rate in Ethiopia in comparison to the previous survey (see Figure 188).

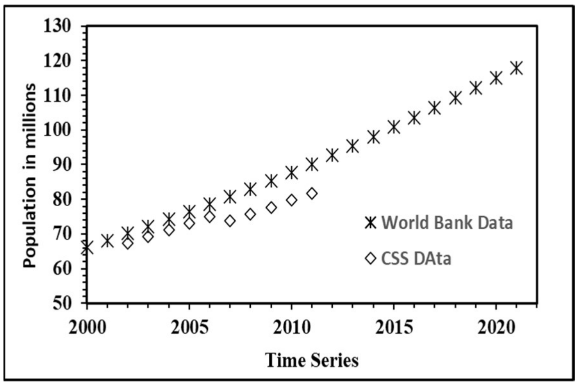


Figure 15 Ethiopian population growth. Sources: [28] and [24]

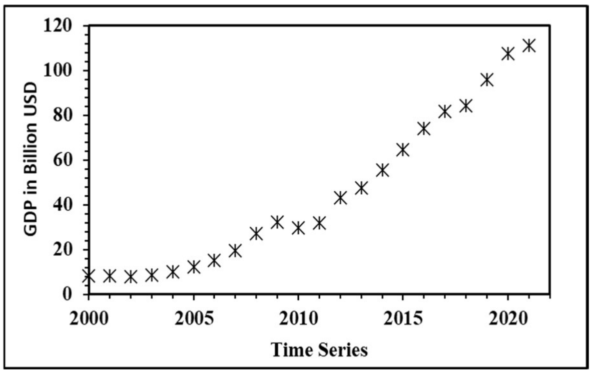


Figure 16 Ethiopia's time series GDP in billion USD. Source: [24]

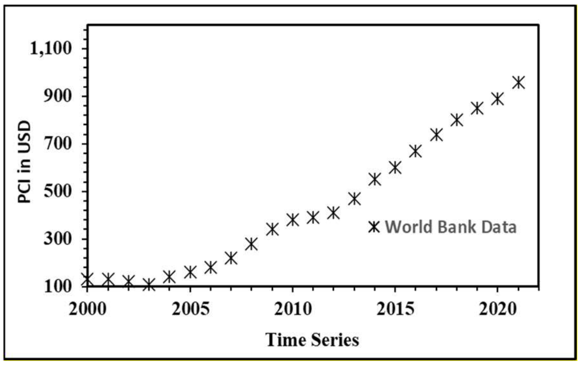


Figure 17 Ethiopia's time series per-capita income in USD. Source: [24]

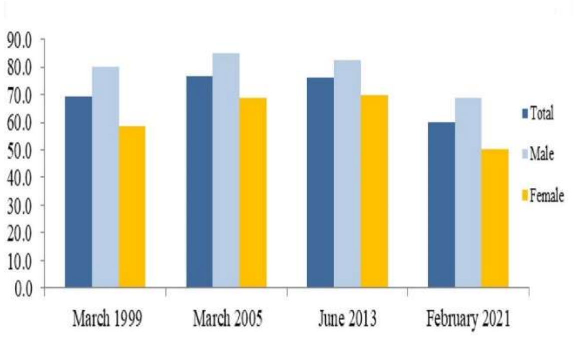


Figure 18 Employment to Population Ratio by Sex during the Four National Labor Force Survey Periods. Source: [29]

A third major driver for the primary energy consumption is the **national energy policy framework**. On one hand, Ethiopia is eager to provide universal electricity access for its residents in the current decade. Therefore, Ethiopia has invested heavily in the electricity distribution network, new hydropower plants (e.g. the great Ethiopian renaissance dam GERD and Gibe III), wind farms (Adama I & II and Ashegoda), geothermal energy generation trials in the Ethiopian rift valley, applications of ethanol as a biofuel blend as well as in solar off-grid solutions. Thus, within a short timeframe of roughly 20 years, almost half of Ethiopia's population gained access to electricity for the first time, and the other half is supposed to follow in the next few years. Likely, this expansion of electricity infrastructure will lead to a steep increase in electricity consumption, a transition from other energy sources towards electric energy and the stimulation of further economic growth.

On the other hand, changes in energy prices have a large impact on energy demand. In Ethiopia, energy prices are set by the government, which has lifted its energy prices in 2022 repeatedly in order to reduce government spending on energy subsidies. As the current prices still only make up for roughly half of the costs, a further price increase of up to 100% can be expected in the next years. While this is bad news for Ethiopian customers and will likely have a dampening effect on energy demand in the short term, it is excellent news for energy producers and for the long-term development of the energy sector.

There are a number of additional energy policy framework conditions that can have a large effect on energy consumption, such as rules and regulations considering:

- Biomass harvesting and land use change
- Foreign investments into energy infrastructure
- Taxation of imported energy infrastructure related goods
- Energy market rules such as feed-in tariffs
- Others

It is difficult to predict, however, how these framework conditions will look like in the mid to long term future. From the current government, further economic reform creating more open market conditions can be expected (e.g. to decrease government subsidies for electricity and fuels). Due to the enormous growth in electricity demand of 30% per year [30], grid stability will continue to be a major challenge.

For this reason, the Energy policy and strategic documents are under revision in 2022 [31]. One goal of the revision is to encourage the private sector to become a major electricity supplier and to encourage renewable energy development from solar, wind, and hydro to facilitate a green energy economy compliant with the Paris Agreement.

Despite the abovementioned potential reforms and significant investments by the government into the national energy infrastructure (Especially the National Electrification Program NEP 2.0 and the construction of the Great Ethiopian Renaissance Dam GERD), energy poverty will likely persist in rural Ethiopia in the foreseeable future. This is nicely reflected in the IEA Ethiopia Energy Outlook 2019 [5], where the current policies scenario predicts the biomass demand in Ethiopia to remain more or less constant over the next decades. In addition to that, the IEA predicts a tripling of fossil fuels consumption and a manyfold increase in renewable energy consumption.

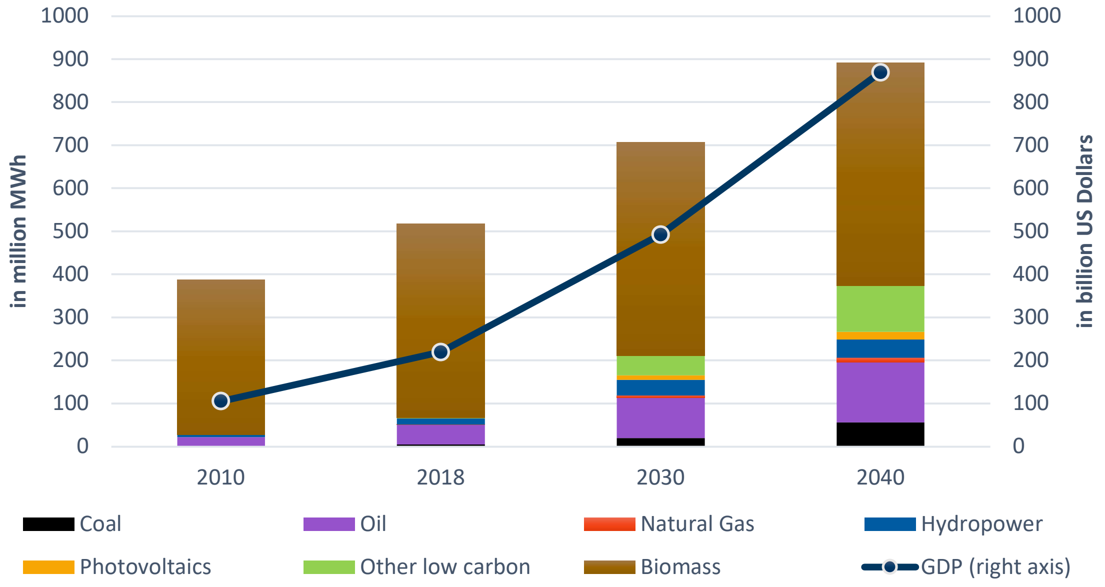


Figure 19 Primary Energy Demand and GDP Development in the base scenario of the Ethiopia Energy Outlook 2019 [5]

All in all, it can be expected that Ethiopia's energy demand will show strong and continuous growth for the upcoming decades and that the energy mix with become more diversified with increasing shares of fossil fuels and renewables except biomass.

1.2.3 Ethiopia and international climate policy

In the year 2021, Ethiopia was responsible for roughly 180 million tons of CO_2 equivalents (MtCO2e) or 0.37% of global emissions according to Climate Watch historical data [27] (see Figure 20). More than half of the emissions stem from agriculture. The energy category is only responsible for roughly 15% of the annual emissions, less than the land-use change and forestry category that reflects the biomass overuse.

The per capita emissions are amongst the lowest of all countries with 1.64 t CO_2e per year.

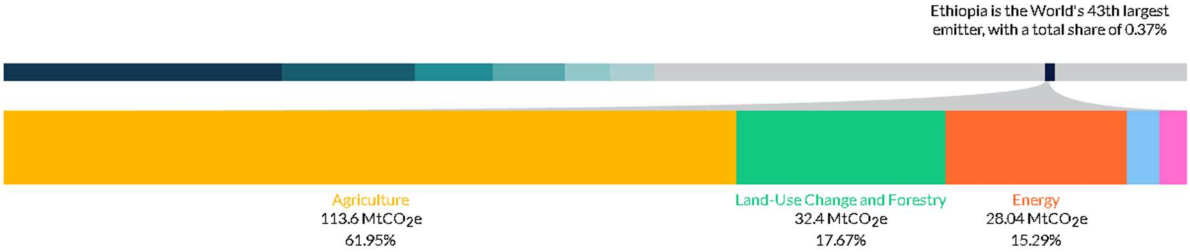


Figure 20 Greenhouse gas emissions of Ethiopia in 2019. Source: [27]

Ethiopia has a long-standing history of supporting international climate mitigation efforts; it has ratified the United Nations Framework on Climate Change in 1994, the Kyoto Protocol in 2005 and the Paris Agreement in 2017. Furthermore, Ethiopia has implemented various national strategies to specify national climate mitigation efforts (such as the Climate Resilient and Green Economy Strategy CRGE and the 10-year development plan). [29]

In compliance with the Paris Agreement, Ethiopia has also handed in a first and an updated version of their Nationally Determined Contributions NDC to the climate targets (see [29]). It strives to reduce national greenhouse gas emission by 69% against the business-as-usual forecast by 2030, which, in-line with IEA predictions as presented in 1.2.2, foresees more than a doubling of present emissions. However, taking into account the stated emission reduction target, Ethiopia aims at reducing its emissions by roughly 50% or 60 MtCO2e to 125 MtCO2e by 2030. This is an extremely ambitious target for a fast-growing low-income economy and essentially requires the leap-frogging of fossil based energy technology. The estimated costs to achieve the NDC are 316 billion USD. 80% of the reduction target is labelled as conditional, meaning that Ethiopia will require roughly 250 billion USD in international support in order to be able to achieve the target. Furthermore, Ethiopia also states in its NDC that it will require support in capacity building and technology transfer in a number of thematic areas such as land use management and green technology. [29]

One key strategy to achieve the NDC is to turn the land-use change and forestry category into a large net sink by restoring up to 15 million hectares of forest and other policy measures. Ethiopia has further expressed a strong desire to participate in international carbon markets as governed by article 6 of the Paris Agreement. [28]

1.2.4 Ethiopia and Power-to-X

P2X has arrived on the political agenda in Ethiopia in 2022, through the GIZ-led Ethiopian-German Energy Cooperation project. It aims at formulating and adopting a national P2X policy strategy framework document (compare with section 1.1.3). Following a preparatory event in early November 2022, a first workshop to prepare for the policy strategy framework document took place on Wednesday, 23rd of November 2022 with numerous high-level government officials and experts. While the policy strategy framework document will only be developed in the upcoming months, it should be noted that Dr. Dinsefa Mensur, local representative of the Solar Fuels project (see section 1.3.4.2), was invited as a local expert and given the space to present the Solar Fuels project as a panelist. The participants highly welcomed the Solar Fuels project and acknowledged the importance of capacity building.

From a current perspective, P2X could play a vital role in achieving Ethiopia's long-term climate targets in numerous sectors such as agriculture, transport, energy and land use change.

1.3 THE SOLAR FUELS PROJECT

1.3.1 Introduction

As has been highlighted in section 1.1, P2X is a key technology to meet the ambitious net zero CO_2-emissions goal by 2050. It can only be reached if all countries participate in the necessary efforts. Hundreds of P2X plants are being planned or implemented at the present time, primarily in western Europe. This equals a potentiation of the present installed capacity and will lead to a decrease in technology costs and efficiency gains – similar to the development of photovoltaics technology in the past decades.

This situation brings about large opportunities for many countries with high renewable energy potential such as Ethiopia (see section 1.2). On one hand, they have comparative cost advantages for P2X implementation in comparison to most western countries due to lower renewable energy costs. Thus, they could act as a supplier of renewable fuels on the global market. On the other hand, P2X can also play a major role in the transformation of the local energy system towards the net 0 emission target and thereby create many well-paid jobs.

1.3.2 Approach

Today, Ethiopia is not prepared to take advantage of P2X as an opportunity. Just like most other low-income countries, there is a lack of know-how and awareness combined with a lack of financial resources. With the present project, we want to tackle these issues by creating a center of excellence for P2X technology at the Adama Science and Technology University.

Thanks to the cooperation with our partners at IET OST, we transfer and create the necessary knowledge for P2X adoption at ASTU. This is done through the joint development of a P2X research and demonstration plant that will be installed and operated at ASTU campus in Adama, Ethiopia. In accompaniment to this, a research program is created and implemented and P2X is extended to the ASTU syllabus.

On the one hand, the demonstration plant will be used to raise awareness considering P2X technology and its potentials amongst decision makers in politics and administration as well as to the private sector and the general public. On the other hand, the plant will be used to do applied research, to educate students and to train professionals.

1.3.3 Objectives

The project’s objectives are:

- Realization of a P2X demonstration and research plant, that is capable to transform the electricity generated from solar panels of the size of a tennis field into a storable fuel.
- Creation of a center of excellence for P2X at the Adama Science and Technology University in Ethiopia that trains 10+ professionals in the field per year.
- Elaboration of blueprint-concepts for the implementation of P2X in the context of Ethiopia, e.g. to substitute biomass as main energy source in rural Ethiopia or to substitute fossil nitrogen fertilizer with green ammonia in agriculture.
- Elaboration of a framework to include abovementioned P2X concepts into international carbon offsetting standards.
- Paving a way for energy transformation and energy diversification in Ethiopia.
- Facilitating studies of how P2X can contribute to the future of Ethiopian and African economy and to gain policy support.

1.3.4 Project Partners

1.3.4.1 Solafrica

Solafrica is a Switzerland based non-profit organization founded in 2009 and located in Bern. Solafrica's mission is to fight energy poverty and mitigate climate change through the promotion of the most abundant renewable energy resource: solar energy. Herefore, Solafrica executes programs and projects in five different categories:

- Vocational Training
- **Innovation and technology**
- Sensitization
- Solar Market Development
- Infrastructure

The geographical focus of Solafrica is sub-Saharan Africa and the Solar Fuels project is the third Solafrica project in Ethiopia. It was initiated as an innovation and technology project to kickstart local capacities in in the field of P2X.

Solafrica carries the Zewo-label, is member of the climate alliance and is aligning its projects with the United Nations agenda 2030 for sustainable development.

1.3.4.2 ASTU Adama Science and Technology University

ASTU was established in 1993 as Nazareth Technical College (NTC), and later on, the college was re-structured as Nazareth College of Technical Teacher Education (NCTTE). In May 2006, the college was promoted to university and named Adama University (AU). In 2011, the Council of Ministers re-structured AU into Adama Science and Technology University (ASTU) with the mandate of a leading role in science and technology to facilitate the socio-economic growth & development of the nation by excelling in applied science and technology fields.

For this purpose, the Materials Science and Engineering (MScE) department started in 2012 having the mission to advance the application of materials through quality education and research, provide need-based and problem-solving community services, and produce internationally competent and ethical graduates who can solve industrial and community problems. Investigation of the role of hydrogen derived products in multi-energy systems & markets and materials development & design for P2X technologies are among the research thematic area of the MScE department.

1.3.4.3 IET Institute for Energy Technology

The IET Institute for Energy Technology is a research and development partner in the field of energy and is part of OST University of Applied Sciences of Eastern Switzerland, located in Rapperswil, roughly 40 km from Zurich. Building on sound specialist knowledge that is imparted to students at bachelor's and master's level, IET is able to carry out demanding and interdisciplinary development projects in the following 6 specialist areas:

- Wind energy
- Electrical power engineering
- Scientific computing and engineering
- Building services engineering
- Applied physics and measuring technology
- **Power-to-X**

The implemented projects in Switzerland and Europe in the field of Power-to-X are realized as development projects in cooperation between industry and research. The IET staff possesses in-depth knowledge of the technologies and economics related to Power-to-X. A team of 14 experienced engineers and scientists conducts feasibility studies and provides advice throughout a project, from planning to implementation. Experts and interested groups can also take part in seminars and guided tours.

1.3.5 Roadmap

The road map for the Solar Fuels project is given in Figure 21.

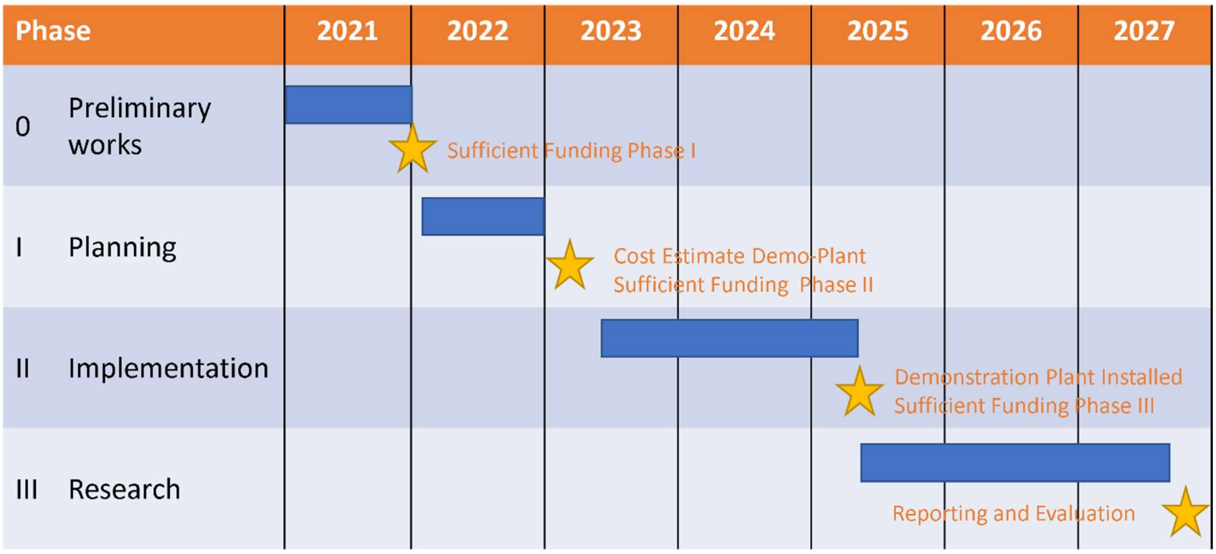


Figure 21 Solar Fuels project road map

1.3.5.1 Preliminary Works

The preliminary works of the project were concluded in 2021 with the securing of sufficient funds for the planning phase. As part of this phase, a first site-independent feasibility study for a P2X plant was created and different project concepts were evaluated. Solafrica decided to follow up on the present concept and managed to secure sufficient funds to start the planning phase by the end of 2021.

1.3.5.2 Planning Phase

Subsequently, the planning phase was started in January 2022 and mostly concluded according to plan by November 2022. The results of the planning phase are summarized in the present report. An overview of the activities that were conducted as part of the planning phase is given in Figure 2222.

The present report is compiled by December 2022. However, some tasks related to phase I are not fully concluded by this time. As it takes time to get quotations from potential suppliers for the P2X research and demonstration plant, the report will be updated upon availability of new insights.

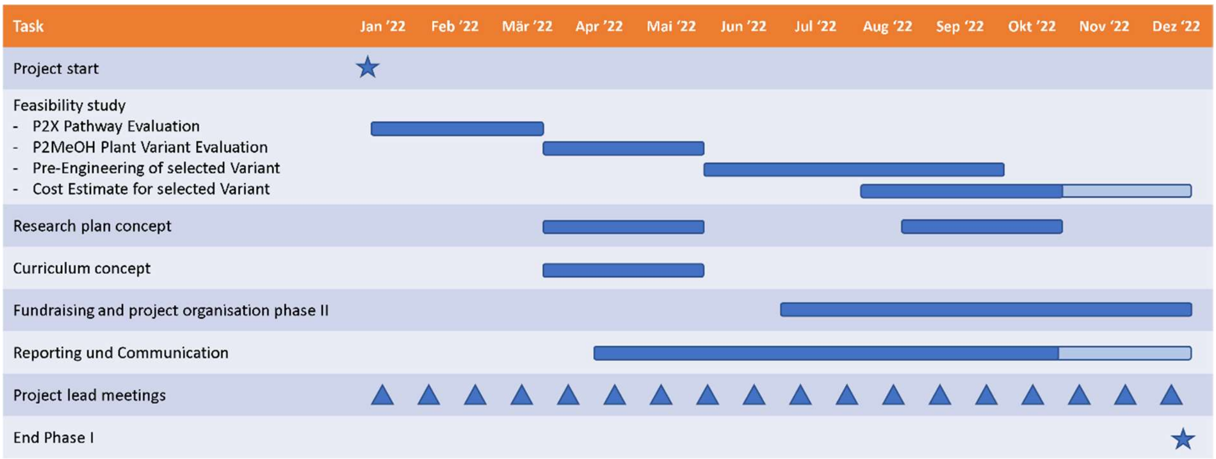


Figure 22 Overview activities phase I

1.3.5.3 Implementation phase

As soon as the minimum funding target for the Implementation phase is reached, the Implementation phase will be started. As part of the implementation phase, the detailed engineering for the P2X research- and demonstration plant needs to be done, before the plant components can be procured, assembled and commissioned. The implementation plan for the implementation phase is given in section 2.5.

1.3.5.4 Research Phase

The Implementation phase will be followed by the research phase that focuses on following through on the previously prepared research program (see section 0). A detailed work program for the research phase will be developed as part of the implementation phase.

2. FEASIBILITY STUDY

2.1 POWER-TO-X PATHWAY EVALUATION

As it has been highlighted in the Introduction section, P2X is a very versatile technology. In principle, there is an indefinite number of potential target products, thus the X can virtually stand for any organic compound. However, only a relatively small number of primary and secondary products are usually referred to as target products of P2X (see section 1.1.2 for description):

- Hydrogen →P2H2
- Methane →P2CH4
- Methanol →P2MeOH
- Di-Methyl-Ether (DME) →P2DME
- Petrol, Diesel or Kerosene →P2FT
- Ammonia →P2NH3

Even though the initial project idea was to create a research- and demonstration plant for P2MeOH, the project team unanimously decided to first take a step back and question the initial project idea by systematically evaluating the different P2X pathways listed above. Therefore, the project team jointly compiled a criteria catalogue and individually evaluated the pathways (by giving grades from 0=lowest score to 10=highest score) before discussing the results and deciding on the way ahead. For the project team to be able to evaluate the pathways according to the criteria catalogue, the experts at OST compiled and distributed the relevant background data to the project team.

2.1.1 Criteria catalogue

To create the criteria catalogue, the project team initially collected a total of 26 potential criteria that were subsequently reduced to the most important 9. This selection was done by asking the individual project team members to rate the criteria according to their relevance (highly important: 4 points – important: 2 points – less important: 1 point – not relevant: 0 points) and then gather and summarize the individual data.

In a second step, the weighting factors for the 9 criteria were determined using two different methods. One weighting factor set was derived from the relevance score that was used to identify the 9 most important criteria, and for the second one, the project team members were asked to individually compare the relevance of the 9 most important criteria to each other (pairwise comparison method). With the second method, a stronger emphasis is put on the criteria that are considered the most relevant. The developed criteria catalogue incl. weighting factors is given in Table 1.

Table 1 Criteria Catalogue for P2X pathway evaluation incl. weighting factors derived

Criteria	Pairwise comparison weighting	Relevance score weighting
High local demand / acceptance for the product	18%	14%
High potential contribution to reducing deforestation	16%	14%
Low hazard potential	11%	13%
High research potential	12%	13%
High availability of feed resources	11%	11%
High international demand / acceptance for the product	4%	10%
Low carbon footprint	7%	10%
High plant efficiency	8%	6%
Low product costs	13%	8%
Total	**100%**	**100%**

2.1.2 Evaluation Results

The average grade of the 6 P2X pathways using the two different weighting sets is given in Figure 23. P2MeOH obtained the highest average score using both weighting sets, followed by P2DME and P2FT. Even though the differences are relatively small, P2MeOH returned the highest individual score for all project team members but two, according to whom P2DME and P2FT perform slightly better.

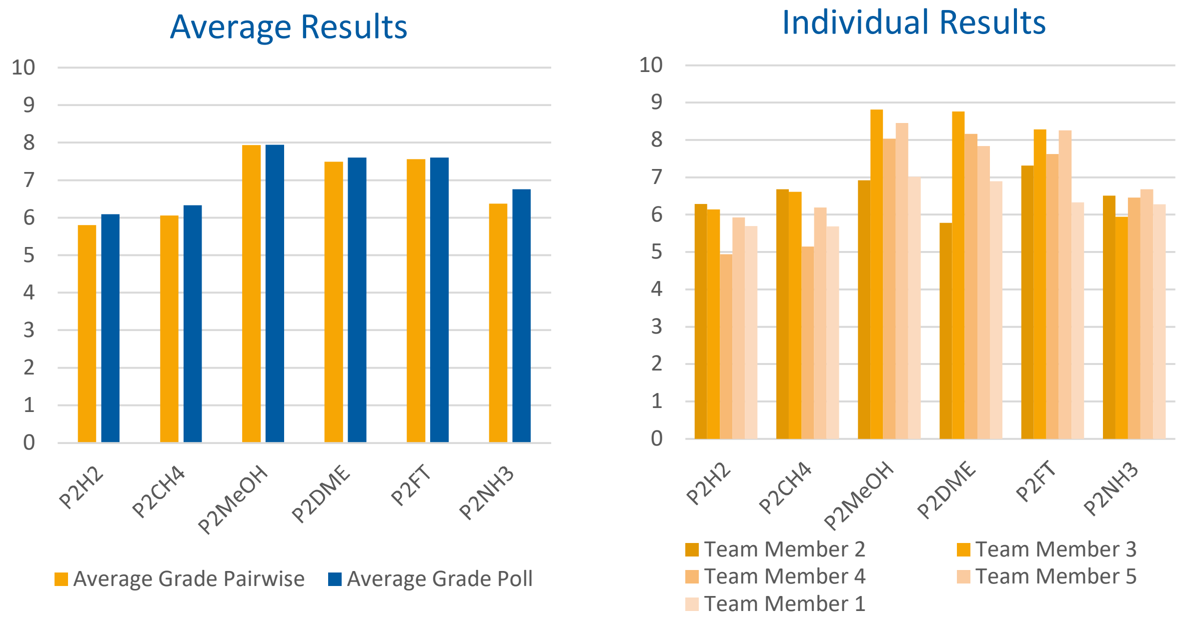


Figure 23 P2X pathway evaluation results

2.1.3 Conclusion

Overall, the evaluation confirmed the initial strategy to build a P2MeOH research and demonstration plant and gave no valid reason to change the target product. The reasons for this are multi-dimensional and complex, but it is noticeable that the paths considered more promising are the "classic" liquid fuels, such as DME, petrol and, in a broader sense, methanol. One main advantage lies in the fact that these energy carriers are already used today in a large number of applications, and they would therefore only require comparatively small changes to present devices and infrastructure. Another main advantage lies in the high volumetric energy density of liquid energy carriers in comparison to gaseous ones, which generally need to be compressed or liquified in for storage and transport purposes.

2.2 P2MEOH PLANT VARIANT EVALUATION

2.2.1 Introduction

A P2MeOH research and demonstration plant can be created in a lot of different ways. In order to define the best variant for the given use case, a number of questions need to be addressed and answered:

- What are the system components?
- What technology should be used for individual components?
- What are the system boundaries?
- What are the overall requirements?

The answering to the abovementioned questions is an iterative process. The core element of this process was the definition and evaluation of a number of variants (see chapter 2.2.2). The results to the abovementioned questions are given in chapter 2.2.3.

2.2.2 Definition of Variants

As a basis for the exploration of potential P2MeOH research and demonstration plant variants, a morphological box scheme was created (see Figure 24). The scheme shows the options for each potential system element, as they have been previously agreed upon by the project team after thorough examination. Through the combination of system elements' options, variants can be created.

The possible combinations are almost endless. However, not all of them make sense, and the use of a technology in one step may limit the choice of technologies in the following steps (e.g. there is no need for an electrolyser if the hydrogen is supplied from an external supplier). For the sake of comprehension, the possible variants described in this report have been limited to three (see chapters 2.2.2.1 to 2.2.2.3) that allow for the exploration of the spectrum of potential variants.

2.2.2.1 State-of-the-art variant (green)

In the state-of-the-art variant, the P2MeOH process is demonstrated as a whole, including the generation of renewable electricity using state of the art technology.
Different options for the renewable energy generation were evaluated including photovoltaics, wind and a combination of the two. For the given boundary conditions (location, foreseen plant capacity), PV is better suited than wind. The evaluation furthermore showed a strong temporal correlation of solar and wind energy potentials. Thus, the option of a combined solar and wind electricity supply was discarded. The variant also includes a grid connection as well as a battery storage system to smoothen electricity supply to the plant.

For water splitting, PEM electrolysis technology was chosen. Although PEM is more costly than AEL technology, it has the advantage of higher conversion efficiency and higher tolerance to fluctuating operation conditions. Furthermore, a hydrogen tank is included in the variant in order to be able to operate the methanol synthesis evenly and provide operational flexibility.

The only system element that does not properly demonstrate P2MeOH is the provision of the carbon source required for methanol synthesis. Since direct air capture of CO2 or the production of syngas

from biomass is costly even in large scale plants, it was decided to use bottled CO_2 from an external supplier as a carbon source in the state-of-the-art variant.
The methanol synthesis is performed using catalytic methanol synthesis. A well-established catalyst is chosen. The process includes the recycling of unreacted CO_2 and hydrogen and the distillation of the produced methanol.

2.2.2.2 Low-cost variant (red)

The low-cost variant does not include the generation and storage of renewable electricity. Instead, the required electricity is drawn directly from the grid. No solar panels, wind turbines, converters or batteries are needed which minimizes the system costs and complexity. However, this also means that the P2MeOH process can only be demonstrated from grid power instead from renewable electricity.
Furthermore, the least costly type of electrolyser (AEL) is chosen for this variant. The carbon source provision and methanol synthesis in this variant do not differ from the state-of-the-art one, since the project team does not see any reasonable low-cost options for these system elements.

2.2.2.3 Experimental variant (purple)

The experimental variant represents the most unconventional and expensive solution. Some of the components would not be used in a commercial plant today because of their low TRL or their high specific costs. From a perspective of applied research, this variant would be very interesting, since it would allow ASTU to explore a number of new technologies including their interaction. However, this would add a lot of complexity to the plant and it is questionable, whether the plant would still be able to provide the foreseen demonstration effect in a satisfying way.

As an electrolysis technology, AEM was chosen. Even though AEM has already been successfully tested on a laboratory scale, there are no commercial scale products yet. Thus, it would be interesting to further develop AEM technology as part of a research project.

The hydrogen storage and compression are based on metal hydride technology. Metal hydrides are capable of storing hydrogen at a very high volumetric density and metal hydride compressors have the advantage of having no moving parts and thus very low maintenance costs. However, the few commercially available products are also very costly. They could be tested for their suitability for methanol production as part of a research project.

The carbon source required for the methanol synthesis is provided by direct air capture of CO_2. This process has recently gained a lot of attention thanks to the successful piloting of the concept by the ETH-Spinoff *climeworks* in Iceland (*https://climeworks.com/roadmap/orca*) and also by serving as the “magic bullet” to reach the net zero CO_2-emission targets by 2050 in many countries’ strategy. However, the technology is very expensive, especially on a small scale, and requires a lot of heat. The integration of DAC into a demonstration plant would add a lot of complexity.
The methanol synthesis uses the same technology as the other variants. However, a novel catalyst would be used.

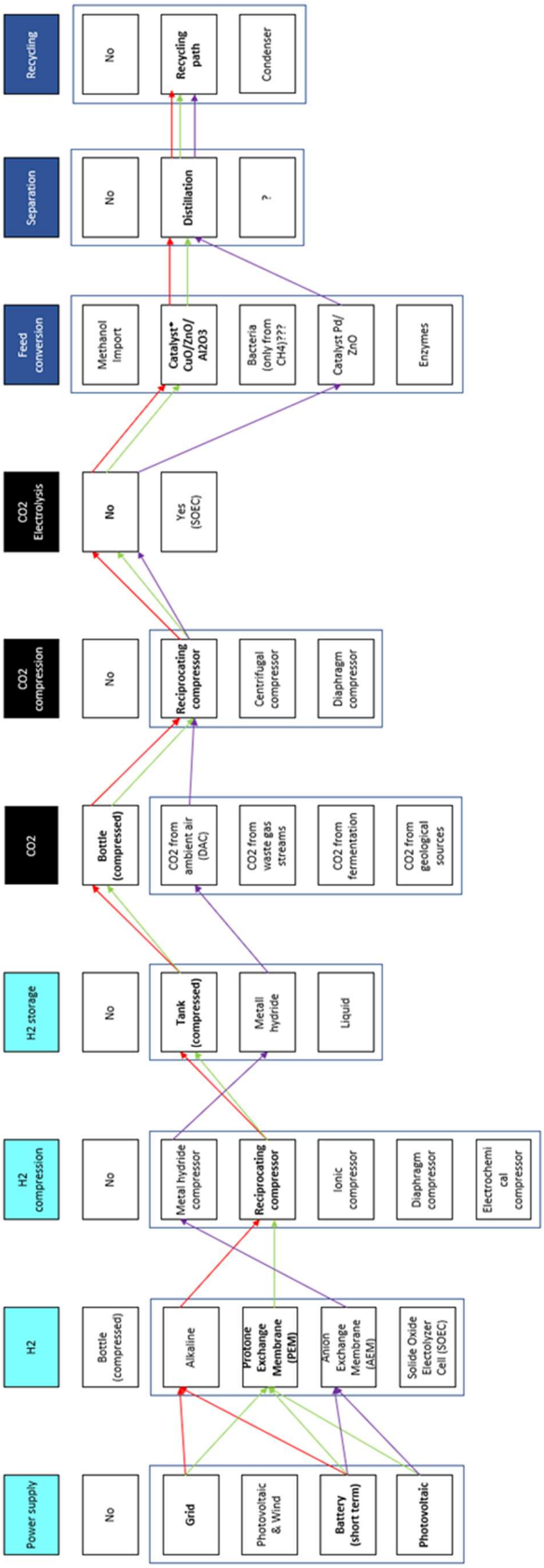


Figure 24 Morphological matrix for P2MeOH variant definition

2.2.3 Results

The decision, as to which of the three variants should be pursued further, was the subject of interesting discussions between the project partners. The experimental (purple) variant as described in section 2.2.2.3 was discarded due to its complexity, associated risk to failing the intended demonstration effect and associated high costs compared to the other two.

The discussion then focused on the main differences between the state-of-the-art (green) variant and the low-cost (red) variant. In essence, a.) whether the demonstration plant should include electricity generation or not, and b.) whether AEL or PEM electrolysis should be used.

The final decision was made **in favor of the state-of-the-art (green) variant** as described in section 2.2.2.1. The main reason for this is, that the project team regarded the demonstration of the process from renewable energy generation to product as crucial for both demonstration and applied research purposes. In addition, if the PV system is not used for methanol production, it can be used to cover part of the energy needs of the campus.

However, it remained open which electrolysis technology should be used. The decision was postponed and made dependent on offers from suppliers. The price/performance ratio should decide which technology is used for electrolysis.

2.2.3.1 System boundaries and system components

An essential element of the variant definition is the scope of the plant and its subsystems including the system boundaries. Furthermore, it must be clear which energy and material flow cross these boundaries in order to be able to plan the necessary infrastructure. The system boundaries for the P2MeOH research and demonstration plant are depicted in Figure 25.

Accordingly, the following inputs are required for the operation of the plant:

- Grid electricity
- Heat and/or cold
- Water
- Carbon dioxide (CO_2)

On the other hand, the plant outputs the following:

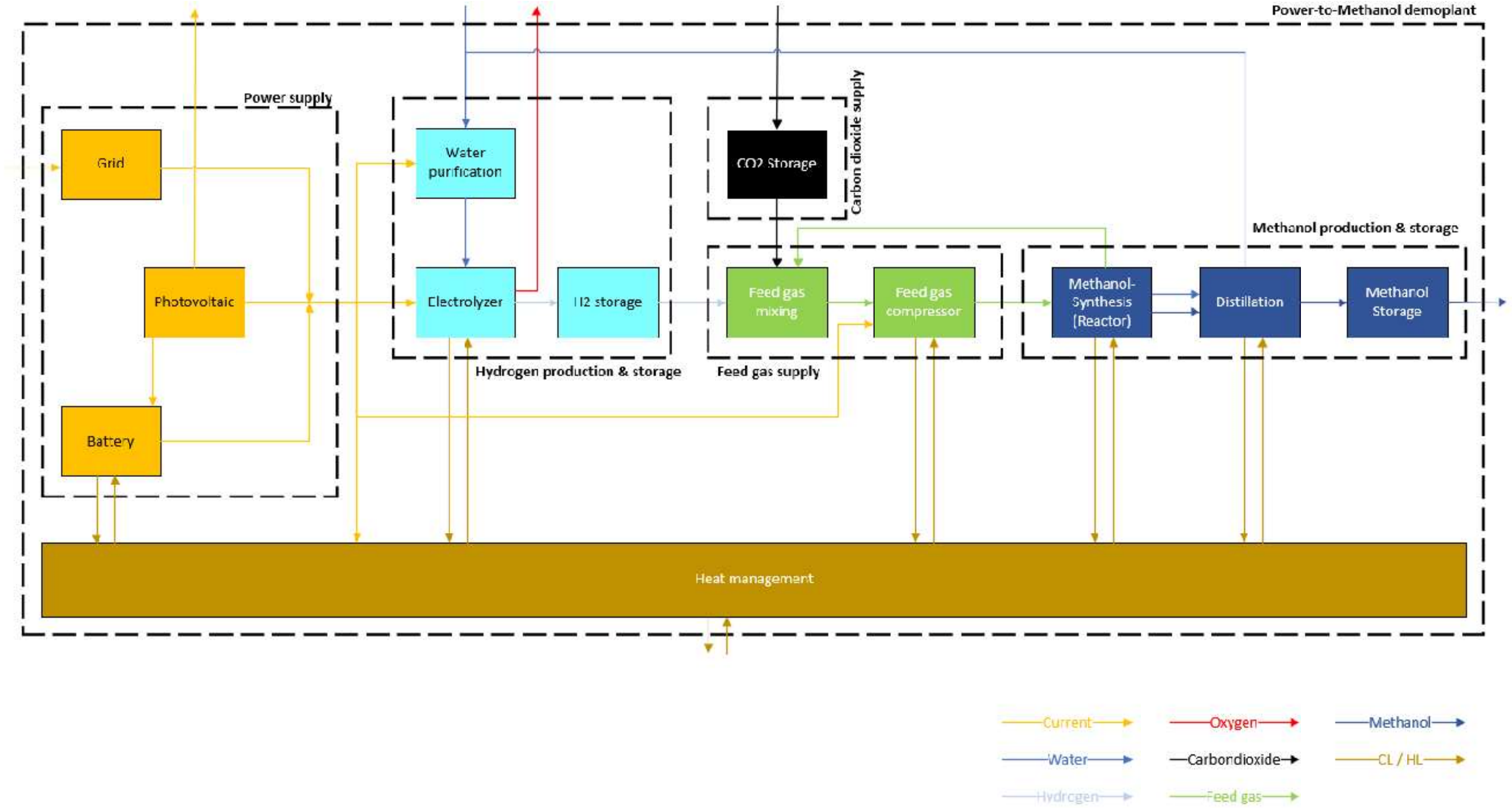
- Methanol
- (waste) water
- Heat and/or cold
- Oxygen

2.2.3.2 Overall Requirements

The overall requirements for the research and demonstration plant have been defined as follows:

- The plant should be able to demonstrate the production of methanol from solar PV as a whole (with the exception of the carbon source) to policy makers, students, researchers and the general public.
- The plant should enable ASTU to flexibly conduct applied research on the subject of P2MeOH (see section 8)

- The plant needs to be designed (and operated) according to modern safety standards (emergency shutdown, explosion protection, safety training). Due to a lack of Ethiopian regulatory framework, European Union standards are used as a reference.
- The plant needs to be integrated into the ASTU campus next to the waste water treatment plant
- The plant needs to take into account the trade-off between affordability and functionality
- The plant needs to run on the electricity it generates itself (not just for the hydrogen generation, also for compression, methanol synthesis, steering, etc.)


Power-to-Methanol demoplant
Power supply
Grid
Photovoltaic
Battery
Water purification
Electrolyzer
H2 storage
Hydrogen production & storage
CO2 Storage
Carbon dioxide supply
Feed gas mixing
Feed gas compressor
Feed gas supply
Methanol-Synthesis (Reactor)
Distillation
Methanol Storage
Methanol production & storage
Heat management
Current
Water
Hydrogen
Oxygen
Carbondioxide
Feed gas
Methanol
CL / HL

2.3 PRE-ENGINEERING SELECTED VARIANT

2.3.1 Framework conditions

2.3.1.1 Space and Location

The research- and demonstration plant is to be located in Adama, Ethiopia, on the campus of Adama Science and Technology University.

Adama is located in the Oromia region of Ethiopia in the Rift Valley, roughly 100 km from Addis Ababa (see Figure 26). Adama is the fourth largest city in Ethiopia with an estimated population of roughly 340’000 in 2016 [21]. The ASTU campus spans an area of roughly 1.5 km^2 and is located in the north-east of the city (see Figure 28). The P2MeOH plant designated location is in the south of ASTU campus next to the ASTU waste water treatment plant and spans an area of roughly 3’000 m2.

Figure 26 Location of Adama

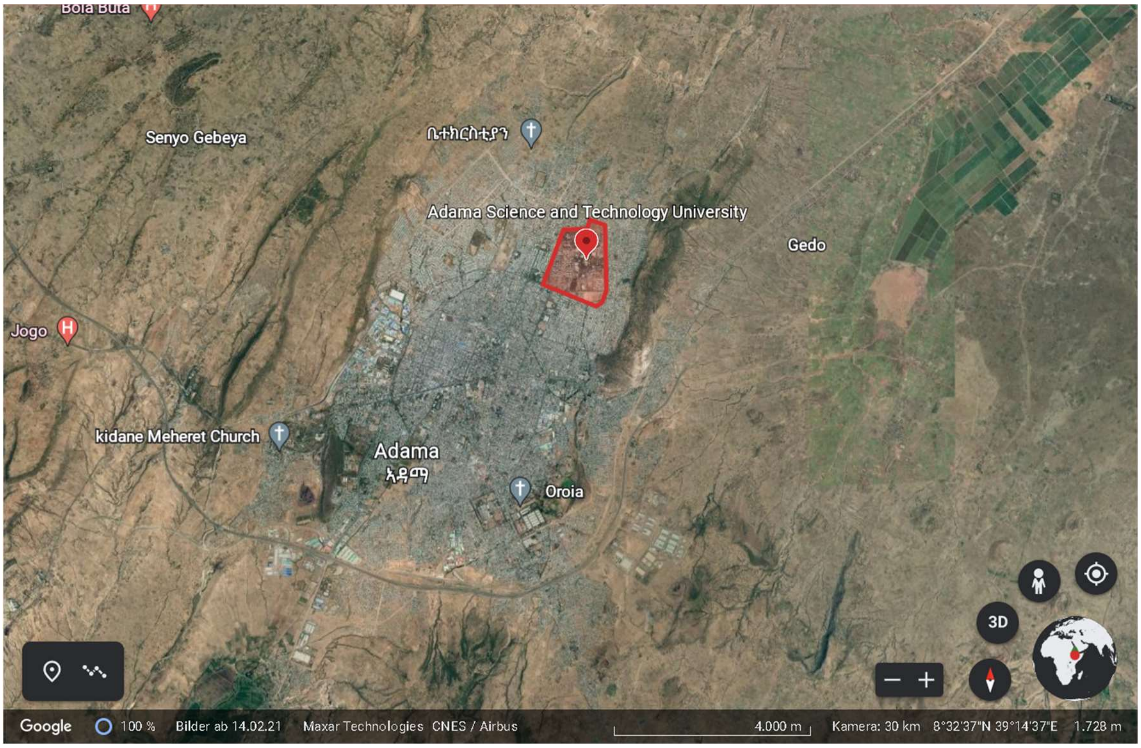


Figure 27 Location of ASTU campus in Adama

Figure 28 Location of the ASTU waste water treatment plan within ASTU campus

Figure 29 Designated Location of the P2MeOH next to the ASTU waste water treatment plant

2.3.1.2 Available infrastructure

The project team is dedicated to make use of existing infrastructure as much as possible. Especially the nearby waste water treatment plant shows a number of potentially interesting synergies. Thus, a number of clarifications have been performed to investigate potential synergies.

Building infrastructure

It has been investigated, whether the plant infrastructure could be integrated into the present building infrastructure of the waste water treatment plant. The investigations showed that unfortunately this will not be possible.

Electricity grid connection

Since the P2MeOH plant should be connected to the grid, it needs to be clarified to what substation and power line it can be connected. These clarifications could not yet be concluded due to the associated bureaucracy and will only be resolved in the upcoming months.

Tap and process water connection

For the operation of the plant (cleaning, service water for operating personnel), a tap water connection is required. Therefore, a connection to the nearby waste water plant will be installed. The process water required for the electrolysis will either be sourced from the tap water connection or from the waste water treatment plant outflow. For both potential water sources lab analysis has been performed (see annex A). For both options, water purification is required in order to meet the quality requirements of the electrolyser.

Waste water connection

The methanol distillation will produce waste water as a side product with relatively low loads of methanol and other small carbohydrates. To ensure proper disposal of this waste stream, a continuous or batchwise connection to the waste water treatment plant inflow needs to be created. The waste water treatment plant is easily capable of handling the projected loads.

Traffic infrastructure

The ASTU campus is well-equipped with road infrastructure. In order to access the designated P2MeOH plant location, only little fortifications and additions to the present access road are required.

Location Preparation

Before starting to build the P2MeOH plant, the location needs to be prepared by removing the shrubs and fortifying part of the surface area with a proper bedding and flooring. In order to secure the perimeter, simple fencing of the plant area is required.

Information infrastructure

The steering and monitoring of the P2MeOH plant requires a connection to the local information infrastructure. A cable connection could be realized via the nearby waste water treatment plant. Alternatively, the plant will be connected via Wi-Fi.

Oxygen use

In order to make use of the oxygen that is created as a side product of electrolysis, oxygen collection is investigated. The oxygen can be used in the waste water treatment plant for the biological purification stage, or, alternatively, for medical purposes. Whether and how the oxygen can be harvested and utilized will depend on the actual electrolysis technology selected for the plant.

2.3.1.3 Photovoltaic energy Potential

Photovoltaic electricity is the designated power source for the P2MeOH plant. Thus, the photovoltaic energy production potential at the designated site was investigated. The actual measurements performed by the Ethiopian National Meteorology Agency served as a basis for this analysis. The average daily solar radiation is depicted in Figure 30, the average monthly solar radiation is depicted in Figure 31.

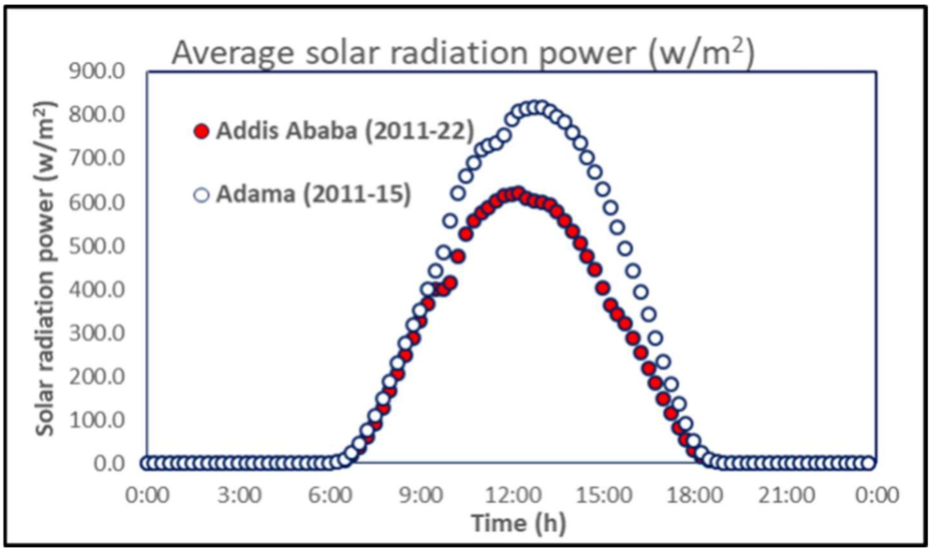


Figure 30 Average daily solar radiation per square meter during the course of a day in Adama and Addis Ababa. Own Analysis based on Ethiopian National Meteorology Agency data.

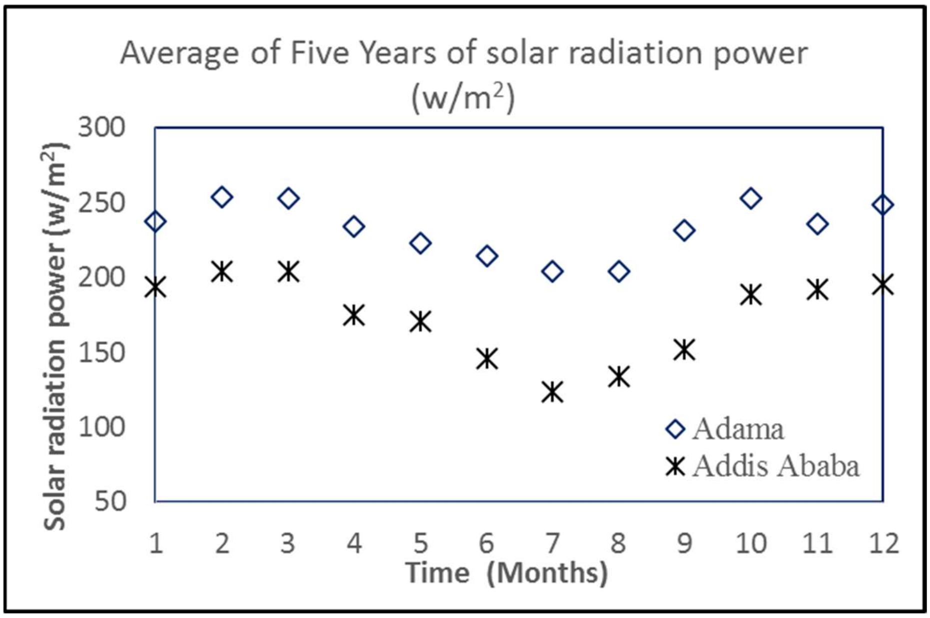


Figure 31 Average solar radiation per square meter on a monthly resolution for Adama and Addis Ababa. Own Analysis based on Ethiopian National Meteorology Agency data.

Adama features an excellent profile for the use of photovoltaic energy. On the one hand, the specific photovoltaic power output is very high with a value of more than 5 kWh/kWp per day[3]. On the other hand, the monthly fluctuations are small thanks to the vicinity to the equator and a generally weak rainy season in Adama.

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[3] for comparison: The specific photovoltaic power output of Zürich, Switzerland is a bit more than 3 kWh//kWp per day according to the global solar atlas (Solargis, 2022)

2.3.2 Use case evaluation

2.3.2.1 *Definition of Use-Cases*

In order to properly select and size all the involved main components, a total of 4 use cases for plant operation are defined and evaluated. Depending on the use case, the requirements for plant components differ significantly. Thus, each use case can be translated to a subvariant of the P2MeOH plant. The overview of the use cases that were taken into account are given in Table 2. System elements that do not differ between the use cases (e.g. the PV system) are omitted. The use cases are briefly described in the following sections.

Table 2 Overview of considered use-cases

Use case	Battery	Electrolysis	H2-storage	Methanol-synthesis
(1)	None	Sunshine operation	No	sunshine operation
(2)	Yes, to smoothen electricity supply from PV	Enhanced sunshine operation	No	Enhanced sunshine operation
(3)	Yes, to redistribute the daily PV production to 24 hours	24h operation from PV and battery	No	24 hours operation from PV and battery
(4)	Yes, to power methanol synthesis and auxiliaries when the sun is not shining	Sunshine operation	Yes, to store the maximum daily H2 production	24 hours operation from PV and battery

(1) Methanol production from PV

The PV system is used to produce hydrogen for the methanol synthesis and power the auxiliary systems such as compressor and heat management directly. The hydrogen produced in the electrolysis is directly fed into the methanol synthesis, which is run whenever hydrogen and electricity are available (“sunshine-operation”). Since grid electricity, battery and hydrogen storage are not included in this configuration, it does not fully represent the selected state-of-the-art variant as defined in section 3.2.

(2) Methanol production from battery enhanced PV

As a main difference to use-case (1), use case (2) includes a battery storage system to enhance operational stability of the electrolysis. Excess electricity produced by the PV system that is not used directly to power the electrolysis or auxiliary systems is stored in the battery system. The hydrogen produced in the electrolysis is directly fed into the methanol synthesis, which is run whenever hydrogen and electricity are available (“battery enhanced sunshine-operation”).

(3) 24 hours methanol production from PV and Battery

In use case (3), PV production is redistributed to 24 hours operation of the electrolysis and the methanol synthesis using a battery storage system. The interaction of battery and PV must be designed in such a way that hydrogen can be produced during the sunshine hours from PV, but battery can be charged at the same time. The battery will take over when the sun is no longer shining.

(4) 24 hours methanol production from hydrogen storage

In use case (4), electricity from PV is not stored in a battery like in use case (3), but in form of hydrogen after electrolysis. The electrolysis is run during sunshine hours like in use case (1). The methanol synthesis can be run continuously, as it is fed from the hydrogen storage and CO2 storage. Excess electricity that is not used by the electrolysis is stored in a battery system to power the continuously operated parts of the plant (compressors, methanol synthesis, auxiliaries). The hydrogen storage is dimensioned to store the maximum expected hydrogen production per day.

2.3.2.2 Discussion and conclusion

In order to select the use case to be represented by the P2MeOH plant, strengths and weaknesses of the 4 use cases have been identified and compared (see Table 3). Additionally, associated costs of the use cases have been briefly estimated.

Table 3 Strengths and Weaknesses of the four identified use cases

Use case	Strengths	Weaknesses
(1) Methanol production from PV	○ Simplest configuration ○ Lowest investment costs (no energy storage)	○ Fluctuating loads for all components ○ Safety relies on availability of grid electricity ○ Very little operational flexibility (all steps are directly coupled) ○ Catalyst degradation due to unsteady operation ○ High costs ○ High costs for daily start and shutdown of methanol synthesis
(2) Methanol production from battery enhanced PV	○ Almost as simple and inexpensive as use case (1) ○ Less load fluctuation as compared to use case (1)	○ Safety relies on availability of grid electricity ○ Very little operational flexibility (all steps are directly coupled) ○ Catalyst degradation due to unsteady operation ○ High costs ○ High costs for daily start and shutdown of methanol synthesis
(3) 24 hours methanol production from PV and Battery	○ Decoupling of PV production and electrolysis / methanol synthesis ○ High operational flexibility ○ Smallest electrolyser size ○ Smallest methanol synthesis size. ○ Safety does not rely on grid electricity primarily	○ Very high battery costs ○ Electrolysis and methanol synthesis are still coupled ○ High overall costs
(4) 24 hours methanol production from hydrogen storage	○ Decoupling of electrolysis and methanol synthesis ○ High operational flexibility ○ Smallest methanol synthesis size ○ Cheaper to store hydrogen than to store electricity ○ Safety does not rely on grid electricity primarily	○ Electrolysis and PV are still coupled ○ High overall costs

Use cases (1) and (2) have significant deficits when it comes to catalyst degradation (methanol catalysts react poorly to fluctuating conditions), operational safety (a safe shutdown of the plant relies entirely on grid electricity) and operational flexibility (All components are directly linked, the methanol synthesis takes hours to be started up and shut down each day). Because the lower costs do not compensate for the inherent weaknesses of these use cases, the project team decided to discard them and focus on use cases (3) and (4).

The main difference between use case (3) and (4) is how the energy is stored. According to the analysis of the project team, the storage of electricity is more costly than the storage of hydrogen. Furthermore, use case 4 allows to run the methanol synthesis decoupled from the electrolysis. This brings about operational advantages as compared to use case (3). The coupling of PV and electrolysis is not regarded as a large weakness, since it allows to avoid electricity transformation.
After careful consideration, the project team selected use case (4) for further elaboration. It shows the best cost/benefit profile of all use cases with a moderate price premium as compared to use cases (1) and (2).

2.3.3 Sizing of Use Case (4)

2.3.3.1 Method

Some of the sizing figures are derived from the in-house developed IET OST P2X tool, which allows to simulate P2X plants in terms of material supply and demand of the different process steps involved. As per writing of this report, no thermodynamics are modelled in the tool. Therefore, other sizing figures such as compressor power and heat management are determined manually based on the mass flows derived by the P2X tool.
As for the power coming from the PV, data from https://www.renewables.ninja/ is used for Adama, Ethiopia. In order to take into account the variability of PV production, each a worst case (3rd of July 2019) and best case (5th of January 2019) PV production day are taken into account.
Further, some of the components respective performance parameters are predefined in order to generate a limited set of sizing configurations:

- 37.5 kg of carbon dioxide is available per day. This corresponds to a commercially available bottle with approx. 51 bar bottle pressure.
- The methanol synthesis reactor’s feed gas conversion rate is 0.2
- The maximum hydrogen production rate of the electrolyser is 4 Nm3/h or about 400 g/h
- 24 hours production means that a continuous production spanning several days (or weeks) is possible

2.3.3.2 Results

The main sizing results for use case 4 are given in Table 4.

Table 4 Summary use case 4

Use-Case	**(4)**
Battery	
Installed capacity [kWh]	280
Max. power output [kW]	46
Electrolyser	
max. H2-prod. [Nm^3/h]	4
max. Power Input [kW]	28
Hydrogen storage	
Norm volume full [Nm^3]	36
H2 mass stored full [kg]	3.24
Norm volume empty [Nm^3]	20
H2 mass stored empty [kg]	1.8
H2 volume storage [m^3]	1.5
Compressors	
Nominal Flow feed [Nm3/h]	2.2
Nominal Flow rec. [Nm3/h]	8.8
Total max. el. Power [kW]	10
Methanol reactor	
Max. Inflow capacity [Nm^3/h]	11
Max. Methanol output [L/h]	0.99
Max. Water output [L/h]	0.44
Total Methanol output [L/d]	23.4

Figure 32 shows the interaction of all essential components during a 24 hours production cycle. The basis is the continuous synthesis of methanol, which in turn requires a constant flow of both hydrogen and carbon dioxide. Hydrogen is produced at maximum electrolysis capacity during the sunny hours and stored temporarily for the darker hours of the day. It follows that much more hydrogen is produced during the sunny hours in order to generate a surplus for the night. This requires electricity from the PV system. Another part of the PV system is needed to run all other systems (especially compressors and heaters) during the sunny hours. However, these systems are also needed at night and therefore the last part of the PV system is needed to generate a surplus of electricity, which in turn is stored in batteries for the dark hours of the day. In this way, the production of approx. 1 L/h of methanol can be achieved.

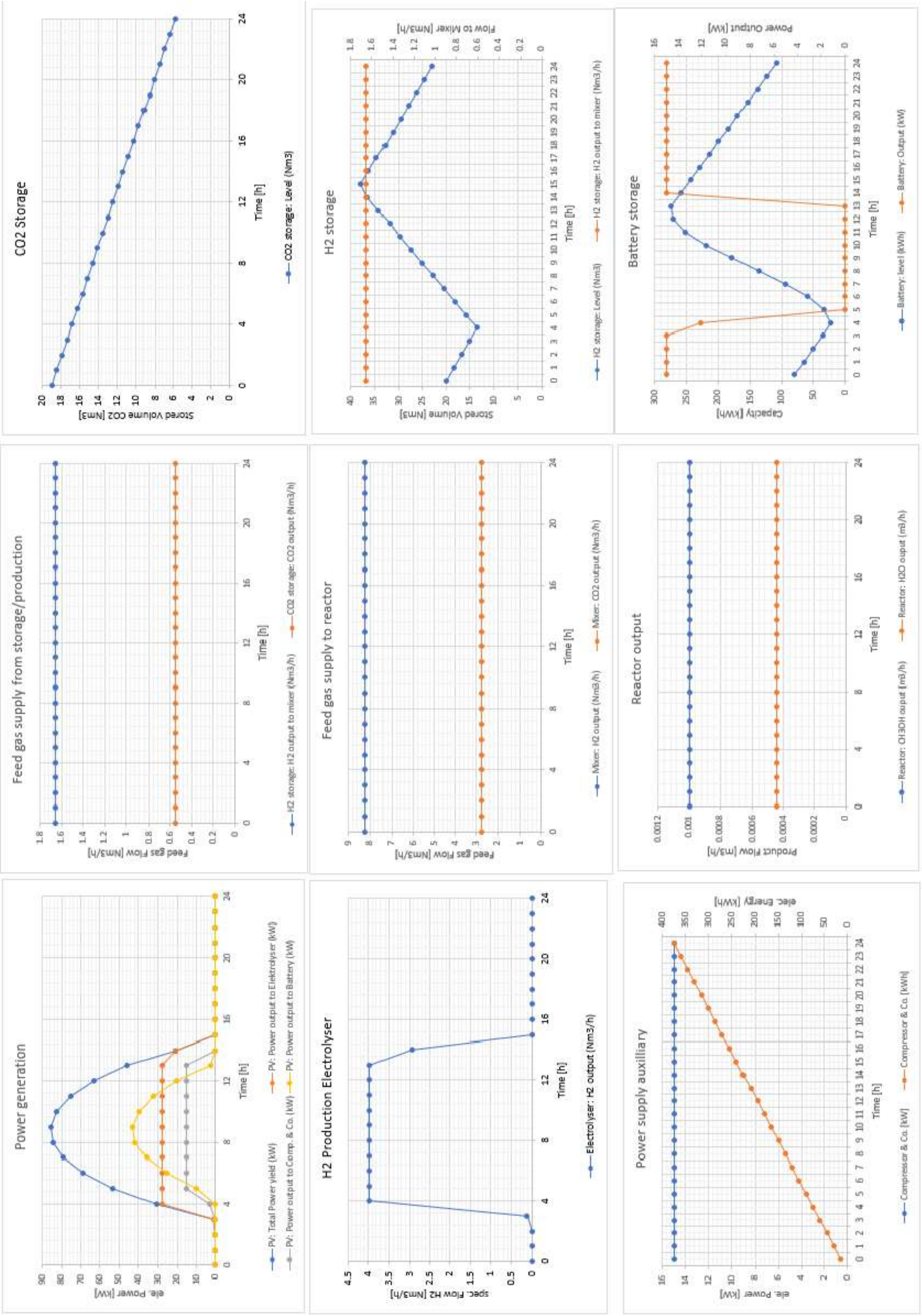

Figure 32 use case (4) production cycle

2.3.4 Main component specification

Once the process is defined in terms of mass and volume flow rates and storage volumes, the thermal design can be tackled. Based on the required process parameters (especially pressure and temperature) for the methanol synthesis reactor, all other components can be defined. This involves complex thermodynamic and chemical calculations that are based on the premise that both the energy and the mass or mass flow must be conserved within defined limits. This means that neither energy nor mass is generated in the system, but only converted. An illustrative example is the reactor. The mass flow at the inlet of the reactor must be the same as at the outlet. The composition of this mass flow, however, must not be, because some of the gases have been converted into methanol in the reactor. For the energy balance, the procedure is similar, with the difference that in the reactor, part of the energy at the inlet is converted into heat due to the chemical reaction in the reactor. It follows that the energy content at the inlet must be equal to the heat generated in the reactor plus the energy content at the outlet. This is a simplified model in order to be able to depict the most important effects.

The result is a process flow chart, which is shown in Figure 33. The following sections present the main considerations on the most important components and process steps that contribute to the plant design.

2.3.4.1 Power supply

The plant is supplied with electricity generated by the integrated photovoltaics system. In consideration of the size of the electrolyzer (see section 2.3.3.2) and auxiliary equipment such as the compressor, a peak power of **100 kWp** was determined. As for Adama, an average electrical output of 0.2 kW/m2 can be expected, an area of roughly **500 m^2** is needed. The specific type of PV system will be evaluated as part of the detailed engineering in the implementation phase.

In order to store the electricity that is not consumed by the electrolysis for the operation of the methanol synthesis and auxiliaries, a battery storage system with a capacity of **280 kWh** is needed. The specific type of battery system will be evaluated as part of the detailed engineering in the implementation phase.

Furthermore, the plant is also equipped with a connection to the local power grid in order to provide additional flexibility and safety. The local grid operates at 220 V / 50 Hz (single-phase) and 380 V / 50 Hz (three-phase).

2.3.4.2 Electrolyser

The hydrogen production rate of the electrolysis was arbitrarily set to a maximum capacity of **4 Nm^3/h**. Based on the IET's experience with their research platform, this is a reasonable size for a demonstration plant because a.) it can be easily accommodated in a container and b.) most of the components for the supporting systems downstream are still commercially available.

The power input for running the electrolysis is estimated to be **7 kWh/Nm^3**. This corresponds to an efficiency of 50% and is considered to be a conservative estimate. Hence, in order to produce 4 Nm3/h, **28 kW** of nominal electrical power is required. Depending on the season, approx. **31-41 Nm3 of hydrogen per day** can be produced from the installed PV system.

The two technologies considered for this demonstration plant PEMEL and AEL. Both are widespread and well-established technologies that are commercially available in the desired capacity (compare with section 1.1.2.1).

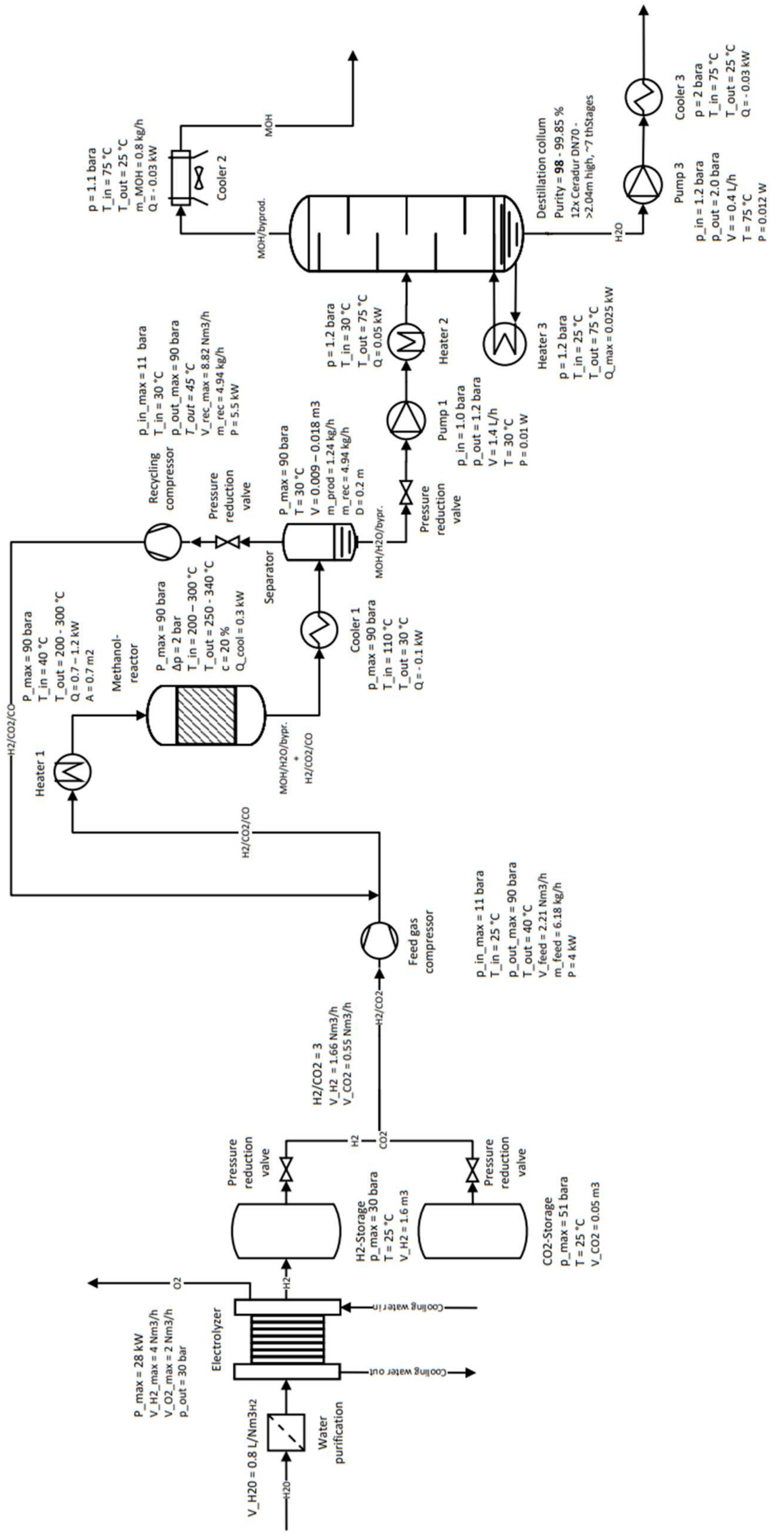

Figure 33 Process flow chart including most relevant process parameter

2.3.4.3 Gas storages

The electrolysis yields hydrogen at a pressure level of approx. 30 bar that is then stored directly. Further compression mixed with carbon dioxide takes place in a later step. This has the advantage that storage tanks of **type I - III (full metal to metal with plastic liner)** can be used which are cheaper than type IV (fibre composite). Hydrogen embrittlement is a problem, but to a much lesser extent at lower pressures than at high pressures. Furthermore, the higher weight of the type I - III tanks as compared to type IV tanks is not a relevant disadvantage for the given stationary application. However, with the current state of global supply chains, availability could be a problem (as the IET has found in other projects). Considering the (theoretically) daily possible hydrogen production from section **Fehler! Verweisquelle konnte nicht gefunden werden.**, a storage volume of roughly **1.5 m^3** is necessary.
The carbon dioxide is delivered to the plant directly in commercially available bottles with approx. 51 bar. They can be connected to the gas mixing unit directly.

2.3.4.4 Gas compressors

As shown in Figure 33, two compressors are needed to get the job done. The feed gas compressor has the task of compressing the mixture of hydrogen and carbon dioxide (feed gas) coming from the storage tanks to the desired synthesis pressure. The recycling compressor, located downstream of the methanol reactor, has the task of returning the feed gases that have not been synthesized into methanol to the methanol reactor. After the pressure increase, these recycled feed gases are combined with the gas flow from the first compressor. Considering, among other things, the costs, availability and TRL, a **reciprocating compressor** is ideal for this task. Two drive concepts are being considered for implementation in a demonstration plant: An electric or a pneumatic drive.

With the electric drive, the piston of the compressor is driven by an electric motor. This is characterized by high efficiency and better controllability. However, the safety requirements and thus the costs are greater because the motor itself can be a source of ignition, which must be technically reduced as much as possible.

A pneumatic drive, on the other hand, is powered by compressed air. Since it does not require electricity, this type of drive is particularly suitable for handling flammable fluids because there are no ignition sources. However, it requires a complete compressed air supply, which is not expensive to purchase but still requires maintenance. The efficiency of such systems is also much lower compared to electric drives.

Figure 34 Example of a compressor as proposed by a possible supplier

Figure 35 Example of a pneumatic compressor [35]

2.3.4.5 Methanol synthesis

The technical implementation of the methanol synthesis is realized by a catalytic reactor. This is essentially a cylindrical container filled with a catalyst material. The reactor is characterized by the inflow capacity of feed gases and the conversion rate. At a **conversion rate of 20%** (which is a typical value for the foreseen catalyst at the foreseen temperature and pressure levels), 20% of the feed gases are converted into methanol. The remaining 80% is recycled and returned to the gas mixer. The exothermic reactions take place according to the following equations and at conditions of **50-100 bar and 200-300 °C:**

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

Both reactions are tied through the water-gas-shift (WGS):

$CO + H_2O \leftrightarrow CO_2 + H_2$

As a result, this means that even carbon dioxide rich feed gases will result in some carbon monoxide being produced in the reactor which in turn further increases methanol yield. The yield can generally be improved by increasing synthesis pressure or reducing synthesis temperature.

The most common and commercially available catalyst material is $CuO/ZnO/Al_2O_3$. This will also be used in the demonstration plant as a default catalyst due to its high availability. At a given space velocity, the reactor can thus also be defined geometrically. An initial contact with a possible supplier for the catalyst material has revealed that approx. 1 kg of catalyst material is required for 1 kg/h of methanol. Considering the bulk density of approx. 1.3 kg/L, this would result in a reactor volume of approx. 0.77 L (periphery of a reactor vessel excluded). However, more detail engineering is required to verify the suggested volume.

As for the type of reactor, an adiabatic fixed-bed reactor is proposed. Since only small amounts of heat are to be expected, this reactor type is a cost-effective solution because it needs little to no active cooling.

2.3.4.6 Methanol distillation

The raw methanol produced in the methanol synthesis contains water, dissolved gases and a quantity of undesired but unavoidable byproducts. The purpose of the distillation unit is to remove those impurities in order to achieve the desired methanol purity specification.

Acetones and ethanol are very difficult to separate by distillation. For this reason, the IMPCA (International Methanol Producers and Consumers Association) defines a purity of 99.85 % by mass for commercially available methanol. However, if it is burnt to cook with, the purity can also be significantly lower. This reduces the number of columns needed for distillation and thus also the costs for this process step. For this reason, a process is proposed (as shown in Figure 33) with only one column.

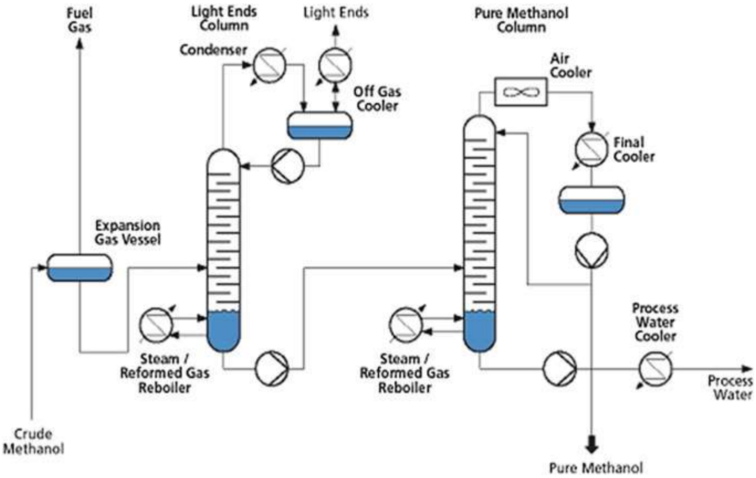

Figure 36 Distillation of high purity methanol [22]

2.3.4.7 Plant Safety

An essential part of the design and construction of any plant is that it is safe in nominal operation. In this context, "safe" means that neither people nor the environment are harmed during a.) normal operation and b.) in the event of a malfunction. Consequently, the plant must either be in a safe condition or be able to be transferred to a safe condition at any time. To this end, it is essential to be aware of the risks involved in operation. Measures should minimize the occurrence of risks or the extent of damage if they cannot be prevented.

The following protective measures should be taken, for example:

- No access to moving parts
- No access to hot surfaces
- No creation of toxic atmospheres
- Protection against explosions

2.4 COST ESTIMATE

The cost estimate for the Implementation Phase is structured in the following subprojects and positions:

- Site preparation and power generation
- Electrolysis and gas storage
- Methanol Synthesis
- Research Plan Development
- Syllabus Development
- Overall Project Management
- Travel Expenses

The overview of the cost estimate is given in Table 5 and Figure 37.

2.4.1 General Remarks

It should be noted that the cost estimate is associated with great uncertainties. Partly, those uncertainties are taken into account by including a budget position for unforeseen costs. However, due to the covid pandemic and the geopolitical situation, the world is facing a.) some significant disruptions in supply chains and b.) inflation rates that have not been seen in industrialized countries for a long time. This led to a clear upward tendency in prices that can have a considerable impact on the costs for the present project. Correspondingly, the presented cost estimate needs to be handled with care. Delivery times are also negatively affected and are subject to significant fluctuation.

Most of the given subpositions are backed by quotes from leading manufacturers. Costs for small parts, sensors, piping, site preparation etc. have been estimated based on experience.

2.4.2 Subproject Site Preparation and Power Generation

In order to be able to set up the P2MeOH plant at ASTU campus, there is some civil engineering and construction work required (compare with section 2.3.1.2):

- Access road
- Electricity connection
- Tap water connection
- Waste water connection
- Fencing of the perimeter

The associated costs for these works have been estimated and amount to a total of 50’000 CHF, of which most will be needed for the preparation of the plant site (30’000 CHF) and the construction of the access road (10’000 CHF) as well as the fencing (7’000 CHF). In order to take into account inflation and unforeseen construction work, the budget position is estimated with 80’000 CHF.

The investment costs of the PV and battery system have been estimated using the sizing figures in chapter 2.3.3 and empirical cost values as reported in literature.

Table 5 Cost Estimate Implementation Phase

A	**Subproject Power Generation and Site Preparation**	**Unit Costs**		**Units**	**Costs**		v	**source**
	Grid connection	CHF	10’000	1	CHF	10’000.00		estimate
	PV-System	CHF/kWp	1’400	100	CHF	140’000.00		estimate
	Battery-System	CHF/kWh	750	280	CHF	210’000.00		estimate
	Site preparation	CHF	80’000	1	CHF	80’000		estimate
	Basic building infrastructure	CHF	100’000	1	CHF	100’000		estimate
	Project Management and Representation	CHF/day	250	250	CHF	62’500		estimate
	Approval process & Tax Exemption	CHF	10’000	1	CHF	10’000		estimate
	Subtotal				**CHF**	**612’500**		
B	**Subproject Electrolysis and Gas Storage**							
	Water purification	CHF	8’000	1	CHF	8’000		quote
	Electrolyzer PEM	CHF	215’000	1	CHF	215’000		quote
	Hydrogen storage	CHF	40’000	1	CHF	40’000		quote
	Overhead sensors, piping, insulation, etc.*	30%		1	CHF	183’900		estimate
	Engineer plant desing/production/commisioning	CHF/day	930	200	CHF	186’000		estimate
	Shipping costs (whole plant, Rapperswil to Adama)	CHF	30’000	1	CHF	30’000		estimate
	Subtotal				**CHF**	**662’900**		
C	**Subproject Methanol Synthesis**							
	Feed gas compressor inc. MFC's	CHF	23’000	1	CHF	23’000		quote
	Recycling compressor incl. separation	CHF	25’000	1	CHF	25’000		quote
	Methanol reactor incl. temperature control	CHF	36’000	1	CHF	36’000		quote
	Methanol distillation incl. heating/cooling	CHF	30’000	1	CHF	30’000		quote
	Methanol storage (incl. in destillation)	CHF	1’000	1	CHF	1’000		quote
	Small parts (Fittings, pipes etc.)	CHF	8’000	1	CHF	8’000		quote
	Frame rack (customized)	CHF	13’000	1	CHF	13’000		quote
	Control cabinet (automation/safety equip.)	CHF	28’000	1	CHF	28’000		quote
	Plant control	CHF	8’370	1	CHF	8’370		quote
	Software package	CHF	7’800	1	CHF	7’800		quote
	Hardware package	CHF	2’000	1	CHF	2’000		quote
	Packaging	CHF	2’500	1	CHF	2’500		quote
	Travel expenses	CHF	3’160	1	CHF	3’160		quote
	Labor Costs	CHF	39’656	1	CHF	39’656		quote
	Reserve	CHF	100’000	1	CHF	100’000		estimate
	Subtotal				**CHF**	**327’486**		
D	**Subproject Research Plan Development**							
	Research Plan Development		CHF	1	CHF	50’000		estimate
	Subtotal				**CHF**	**50’000**		
E	**Subproject Syllabus Development**							
	Syllabus Development		CHF	1	CHF	50’000		estimate
	Subtotal				**CHF**	**50’000**		
F	**Overall Project Management**							
	Overall Projet Management	CHF/day	850	200	CHF	170’000		estimate
	Communication and Fundraising	CHF/day	850	60	CHF	51’000		estimate
	Project Administration	CHF/day	850	20	CHF	17’000		estimate
	External Expertises	CHF	40’000.00	1	CHF	40’000		estimate
	Subtotal				**CHF**	**278’000**		
G	**Travel Expenses**							
	International Flights	CHF	1’500.00	8	CHF	12’000		estimate
	Accomodation and Catering	CHF/day	100	100	CHF	10’000		estimate
	Subtotal				**CHF**	**22’000**		
H	**Unforseen Expenses (20%)**				**CHF**	**400’577.20**		estimate
	Total Costs Implementation Phase	***Total Costs***			***CHF***	***2’403’463***		

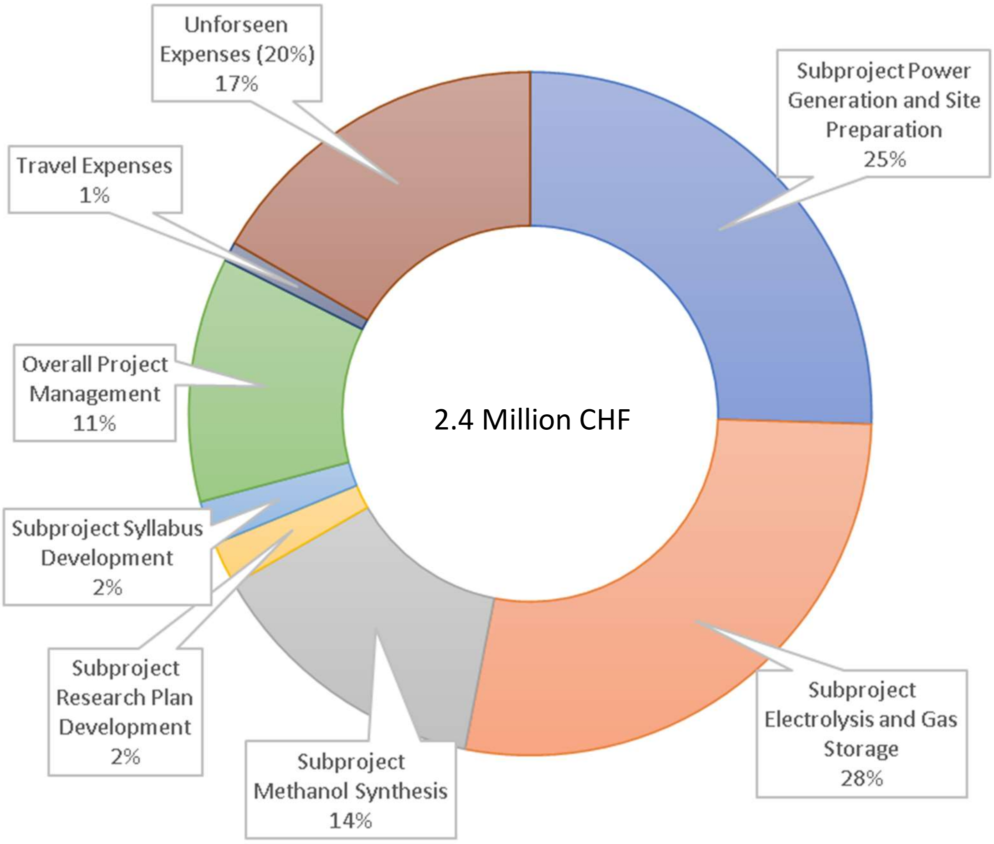

Figure 37 Cost structure the implementation phase budget

The subproject will be led from Ethiopia through our local representative Dr. Dinsefa Mensur and also includes, in addition to the project management for site preparation and the power generation infrastructure, advocacy work on behalf of the project. Last but not least, the government approval process following the given agenda is included:

- Presentations of the Feasibility Study Results in front of
    1. The University Senate
    2. The University Board
    3. Government Officials of Adama, Oromia and Ethiopia
    4. Public
- Preparation and signing of Memorandum of Understanding between Solafrica and ASTU
- Securing of tax exemption to import the P2MeOH Demonstration Plant

2.4.3 Subproject Methanol Synthesis

The subproject Methanol Synthesis includes the detailed engineering, construction and installation of the methanol synthesis and the process control. The subproject Methanol Synthesis will likely be covered by an external supplier with corresponding experiences. The given cost estimate is based on a supplier quote.

2.4.4 Subproject Electrolysis and Gas Storage

The subproject Electrolysis and Gas Storage covers the remaining infrastructure that is not included in the previously described subprojects:

- The factory acceptance testing of the methanol synthesis at the Rapperswil site of IET OST
- The procurement, testing and integration of the electrolysis and gas storage equipment into the plant
- The preparation for the integration of the PV and battery system into the plant
- The preparation for shipping, the shipping and the local installation (incl. site acceptance testing) of the plant at the ASTU site in Ethiopia.

2.4.5 Research Plan Development

In parallel to the commissioning and construction of the research and demonstration plant, the research plan is further developed. Here fore, the identified key areas of research are further detailed into working packages and potential research partner are evaluated and approached.

2.4.6 Syllabus Development

In the syllabus development subproject, an overview of existing lectures in relevant fields at ASTU is created and evaluated for potential gaps and opportunities for improvement. Here we can profit from the vast materials and experiences at IET OST with regards to teaching in the area of P2X.

2.4.7 Overall project management

The costs for overall project management (coordination, controlling, reporting, fundraising, communication, quality assurance) have been estimated based on the total costs and empirical values.

2.4.8 Operational Expenses

The operating expenses OPEX depend largely on the actual equipment that will be commissioned and the detailed research plan. Thus, the OPEX will be determined as part of the implementation phase. However, in order to have an idea of the likely operational expenses today, an estimate for fixed and variable cost is created as part of the planning phase and provided hereafter.

2.4.8.1 Fixed OPEX

Fixed OPEX are all costs that remain constant over time and usually cannot be avoided. They are usually unrelated to the actual production. In relation to this demonstration plant, fixed OPEX are incurred for the following:

- Insurance
- Maintenance and repairs (labor and equipment such as fittings etc.)
- etc.

As a rule of thumb, the annual fixed OPEX for the operation of a plant amount to approx. 3% of the CAPEX per year. However, as in the present case we will not have to pay for amortization and location rent, that usually make up a large part of the fixed OPEX, we estimate the fixed OPEX to be 1% of the CAPEX or roughly 15'000 € per year.

2.4.8.2 Variable OPEX

Variable OPEX, on the other hand, are directly linked to production volume. In relation to this demonstration plant, variable OPEX are incurred for the following:

- Energy (electricity, if drawn from the grid)
- Utilities (water, waste)
- Material inputs (carbon dioxide, nitrogen to flush the methanol synthesis reactor, lubes, etc.)
- Consumable materials such as catalyst for methanol synthesis and lab equipment
- Etc.

As it is not clear today, how consistent the P2MeOH plant will be operating, it is difficult to give an adequate estimate of variable OPEX costs. Es a first rough estimate a variable OPEX of 2% of the CAPEX or roughly 30'000 € per year is estimated. It remains to be negotiated and defined who will be covering the variable OPEX costs for the plant.

2.5 IMPLEMENTATION PLAN

2.5.1 Pre-Requirements

The implementation phase can only be started when sufficient funds for the project are secured. In essence this means that at least 75% of the total costs for the implementation phase or 1.5 Million CHF need to be secured at first. Although the fundraising process is already ongoing (pre-talks with a number of foundations and governmental stakeholders) and some contributions have been put in promising, definite agreements can only be reached after provision of the present report.

2.5.2 Proceedings

Based on our talks with potential suppliers and in-line with the budget estimate given in section 2.4, it is assumed that the methanol synthesis part of the plant as well as the process control hard- and software will be built by a specialized pilot plant builder. It will be designed and built at the site of the supplier in coordination with the overall project management, before being shipped to the IET OST site in Rapperswil for factory acceptance testing and integration of electrolysis and gas storages to the process control system, which will likely be designed and commissioned through IET OST. Finally, the system will be shipped to the ASTU site for site acceptance testing and integration of the PV and battery system, which will be commissioned though ASTU.

It is foreseen for an ASTU representative to join the IET team for factory acceptance testing and integration of electrolysis and gas storage into the process control system and for an IET OST representative to join the ASTU team for site acceptance testing and installation.

In parallel with the construction of the research and demonstration plant, the project team will also further develop the research plan and ASTU syllabus, in order for it to be ready by the time of the installation of the plant.
Herefore, the identified key areas of research are further detailed into working packages with specific research questions. Furthermore, potential research partners are evaluated and approached. In order to improve the ASTU syllabus, an overview of existing lectures in relevant fields at ASTU is created and evaluated for potential gaps and opportunities for improvement. Here we can profit from the vast materials and experiences at IET OST with regards to teaching in the area of P2X.

2.5.3 Organization

The project will continue to be led by the project lead committee that consists of one representative from each partner institution. The project lead committee will be chaired by the Solafrica representative, who is also responsible for the overall project management (controlling, reporting, meeting management, planning, etc.). The project's organizational chart is given in Figure 38.

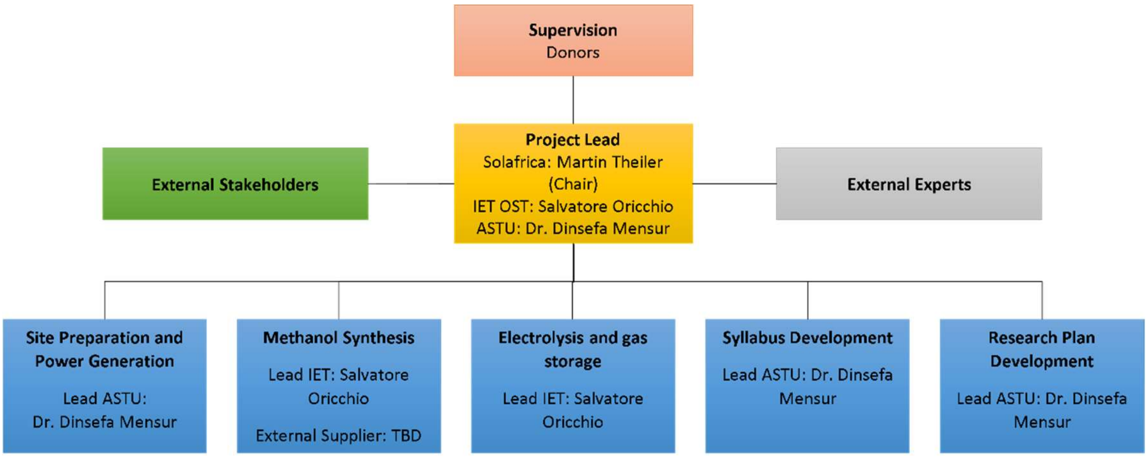

Figure 38 Organizational Chart of the implementation phase

2.5.4 Schedule

As we do not have a definitive agreement with potential suppliers by today, the current schedule (see Figure 39) needs to be considered as provisional.

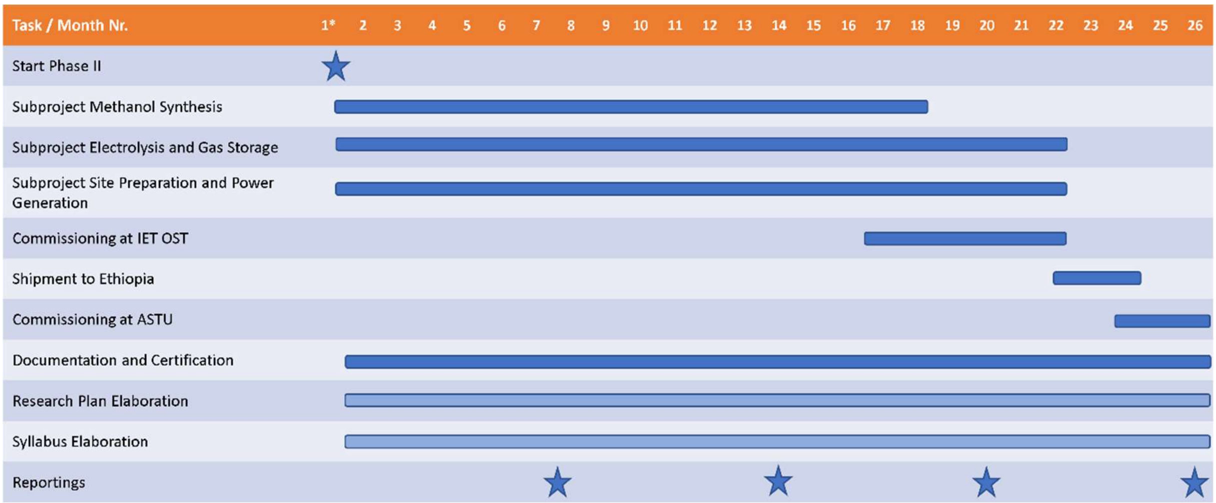

Figure 39 Rough provisional schedule Phase II

3. RESEARCH PLAN CONCEPT

As an integral part of the planning phase, the project team has created a concept for the research it foresees to carry out with the P2MeOH research and demonstration plant (see section 2.3.5.2). The research plan concept has been developed in parallel to the P2MeOH Variant evaluation as soon it was clear, that the research and demonstration plant will be representing the P2MeOH pathway. This way it is made sure that the P2MeOH plant can fulfill its designated purpose as a research facility. To develop the research plan concept, the project partners have created a shortlist of potential research topics and then selected the 7 most relevant and promising key areas for research (see section 3.1).

3.1 KEY AREAS

The list of identified key areas for research are given in Table 6.

Table 6 Key areas of research as part of the research phase of the Solar Fuels project

Key area of research	Short description of foreseen activities
P2MeOH Optimization	The operation of a research and demonstration plant is a continuous process of trial and error to optimize all the included elements and their interplay that will be the core element of the research phase.
Catalyst development	Design, synthesis, production and evaluation of catalyst materials and recipes for methanol synthesis and electrolysis.
CO_2-sourcing	Assessment of available CO_2 sources in Ethiopia and design and testing of lab-scale CO_2 production unit.
Application of methanol	Modification and testing of locally available cookstoves for methanol fuel, assessment of methanol as a chemical feedstock in the Ethiopian industry and assessment of social acceptance for methanol as a cooking fuel
Life Cycle Assessment	Life Cycle Assessment of cooking with the solar fuel methanol in comparison to prevailing biomass-based alternatives and preparation of a carbon offsetting-scheme based on the replacement of biomass with methanol.
Economics of P2MeOH	Assessment of the presumed costs for commercial scale P2MeOH implementation in Ethiopia.
Advocacy and Promotion	Participation in national and international forums and events, Organization of a national forum for the topic P2X, Organization of media events and writing of publications, Supporting the government in the preparation of guidelines and other strategic document considering P2X technology Impact assessment on the advocacy activities

The selected key areas of research span a wide variety of topics such as engineering and process optimization, applied material sciences, social sciences, ecological system design and advocacy and promotion. The project team foresees to set up collaborations with a variety of other research institution, governmental and civil society organization in order to successfully implement the research plan.

One first loose collaboration was already established with the Institute for Ecological System Design IES of the Swiss Federal Institute for Technology in Zürich ETHZ: A master student will compile a first life cycle assessment as depicted in the research plan concept. This thesis will help the project team to get a better understanding of the carbon flows associated with cooking with biomass vs. solar fuel methanol and will be the basis for further activities towards monetizing potential greenhouse gas benefits of P2X in commercial scale applications in Ethiopia.

Furthermore, it should be noted that the catalyst development lies within the core competencies of the Department of Material Sciences at ASTU. The P2MeOH infrastructure will allow ASTU to test its lab-scale developments under real-life conditions.
The research plan will be elaborated in further detail as part of the implementation phase.

3.2 BUDGET

The budget for the research phase will be determined as part of the implementation phase based on the further elaborated research plan.

4. SYLLABUS

Education and research are keys to adopting, adapting, improving, and innovating technology. ASTU, as one of two science and technology universities in Ethiopia, works eagerly to develop into a regionally leading education and research institution in the fields of energy diversification and specifically P2X technology. By establishing a training center for future professionals who will work to improve the P2X technology, i.e., efficiency, cost reduction, system integration, catalyst development and design of the P2X plants, ASTU strives to serve as a training, teaching, and research hub for Ethiopia and East Africa in the mid to long term future.

Therefore, courses/syllabi that enable students to start their research careers in the green hydrogen-related topic have to be included/revised in the existing curriculum. The syllabi have to include but are not limited to fundamentals of electrolysis, classification of electrolysers, selection & sizing electrolyzers, hydrogen application, source of power supply, Mechanisms to lower hydrogen production cost, selection and sizing hydrogen tank, selection of compressors for hydrogen plant, hydrogen production plant and infrastructure design, hydrogen derived fuels, chemicals, and transportation.

For this purpose, the present teaching materials, syllabi and university curricula have to be revised with the support of experienced professionals from IET OST, ASTU and other institutions. The related laboratory facilities for P2X research are developed with the IET OST expert's supervision and support.

Moreover, to strengthen the center's collaborative work and support, for example, course teaching either virtual/in-person, short-term research visits, supervising/advising Ph.D. students from IET OST, and another experienced institution in P2X is needed. The road map for the P2X training syllabi and laboratory development is given hereafter.

Table 7 Road Map for the syllabus and laboratory development

Task	Timeframe	Remarks
Syllabi Revision	2023 - 2024	IET OST, ASTU & Solafrica
P2X Laboratory Development	2023 - 2025	IET OST, ASTU & Solafrica
Training Materials Development and Adaptation	2024-2024	IET OST, ASTU & Solafrica
Teaching, Advising Ph.D. students and short-term visits	Upon demand and availability of suitable collaborators	IET OST, ASTU, other research institutions & Solafrica

5. CONCLUSION AND OUTLOOK

The present report emphasizes P2X as a key technology to meet global greenhouse gas emission targets. Thanks to the ongoing and forecasted rapid market development, it can be assumed that specific investment costs will significantly go down and performance parameter will significantly go up in the upcoming decades. For many LDCs with high renewable energy potentials, such as Ethiopia, P2X presents a large market opportunity to modernize their own energy infrastructure and to export synthetic fuels to other countries.

The Ethiopian energy sector is growing strongly. At the same time, Ethiopia strives to reduce GHG emissions by 50% in comparison to today. This is a challenging task and will require large efforts in all kinds of sectors. In order to transform the biomass from the largest CO_2 source into a large sink as planned, huge efforts are required. Amongst other things, consumers need to be presented with affordable alternatives to biomass as an energy carrier. Here is where we see one potential use case for P2X in Ethiopia; in the substitution of biomass as an energy source for cooking. However, Ethiopia is not prepared to make use of this chance today as it lacks the required know-how as well as awareness in politics and the general population.

In order to overcome these deficits and to make a first step towards the adoption of P2X technology in Ethiopia, the Solar Fuels project was developed. It aims at establishing a center of excellence at ASTU through knowledge transfer, the realization of a research and demonstration plant and the implementation of an international research program.

In the planning phase of the Solar Fuels project, a feasibility study for the research and demonstration plant was carried out. As a first step, the P2X pathway to be demonstrated was verified. In a second step, different variants for the selected P2MeOH pathway were evaluated. For the most promising variant, several use cases were evaluated. Afterwards, the components for the plant were defined and dimensioned and a first process flow diagram was created that served as a basis for obtaining quotes from potential suppliers. Whereas no supplier could be found that would be willing to deliver the plant as a whole, many suppliers could be found that are willing to deliver parts of the plant, e.g. the methanol synthesis. Based on the supplier quotes and empirical values, the total costs for the implementation phase are estimated to be roughly 2 Million CHF or 2.4 Million CHF respectively, when taking into account 20% reserves for unforeseen expenses.

Based on the planning phase results, the fundraising for the implementation phase will be intensified in the first months of 2023. The implementation phase will be started based on the availability of sufficient funds. For the present project, a total of roughly 1.8 Million CHF need to be secured before the implementation phase can be started.

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7. APPENDICES

A	Water Analysis Results for Groundwater and treated ASTU Wastewater
B	PhD Curriculum on Materials Science and Engineering