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Research project SHELTERED

Sustainable cHEmicaL Transport fuEls foR SwitzErlanD

Technology Specification Report of Low Carbon Fuels

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Paul Scherrer Institut

Laboratory for Energy System Analysis

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Contents

Table of Abbreviations

LCF	Low Carbon Fuels
RCF	Recycled Carbon Fuels
BtX	Biomass to X fuels/Biofuels
PtL	Power to Liquid fuels
PtX	Power to fuels
StL	Sun to Liquid fuels
RE	Renewable Electricity
AEC	Alkaline Electrolysis Cells
PEM	Polymer Electrolyte Membrane electrolysis cells
SOEC	Solid Oxide Electrolysis Cells
HHV	Higher Heating Value
LHV	Lower Heating Value
H_2	Hydrogen
ASU	Air Separation Unit
SMR	Steam Methane Reforming
FT	Fischer-Tropsch
MeOH	Methanol
RWGS	Reverse Water Gas Shift
SNG	Synthetic Natural Gas
FAME	Fatty Acid Methyl Ester
UCO	Used Cooking Oil
HVO	Hydrogenated Vegetable Oil
DME	Dimethyl Ethel
SR (+)	Solar Reforming (plus)
ST	Solar Thermochemical
ATR	Auto Thermal Reforming
CCS	Carbon Capture and Storage
NGD	Natural Gas Decomposition
CLRa	Auto-thermal Chemical Looping Reforming
PSA	Pressure Swing Adsorption
CE	Conventional Electrolysis
HTE	Higher Temperature Electrolysis
FTR	Fired Tubular Reformer
LH_2	Liquid Hydrogen
LOHC	Liquid Organic Hydrogen Carriers
TRL	Technology Readiness Level
CAPEX	Capital Expenditures
TEA	Techno Economic Assessment
LCA	Life Cycle Assessment
ESM	Energy System Model
SDGs	Sustainability Development Goals

1. Introduction

In order to achieve Switzerland's goal of carbon neutrality by 2050, low-carbon fuels (LCFs) will play an essential role in the emission reduction of transportation and aviation systems and the decarbonization of the energy system. Transport modes and other applications that cannot be electrified are likely to rely on liquid or gaseous low-carbon fuels to reduce greenhouse gas emissions in the future. Therefore, the SHELTERED project aims to evaluate the role and perspectives of sustainable chemical transportation fuels within a “net-zero” Swiss energy system.

The term “low-carbon fuels” includes a wide range of fuels and technology routes, and their production and evaluation are limited by many factors such as energy demand, resource potential, geographical location, transportation costs, production costs, etc. In order to consistently evaluate the production processes, supply chains and geographical factors, it is necessary to establish a unified low-carbon fuel matrix. Table 1 summarizes the basic information on low-carbon fuel categories to provide an overview of low-carbon fuel types. The main categories are Biofuels (BtX), Hydrogen, Ammonia, Power to liquid fuels (PtL), Sun to Liquid Fuels (StL), and Recycled Carbon Fuels (RCF). This report covers their relationships, applications and brief characteristics. The potential and availability column summarizes the current opinions from the literature and comments on the general potential of these fuels.

Table 2 gives an overview of all the LCF technologies introduced in the LCF analytical matrix, separated by electrification or non-electrification for further analysis. Many technological paths have been developed and used, and the fuel production methods used in different plants differ. The principle of screening LCF production routes is to include all technologies as well as possible and have strong representativeness and potential. The standardization of the technical route is a summary based on literature and reports to ensure that it can be evaluated in a modular and unified way.

The technology specification report concludes the first subtask in the SHELTERED project WP1. The purpose of this report is to serve as the basis for sustainability assessment of LCFs, summarize standardized technical processes and parameters, and provide a framework of analysis objects for subsequent economic assessment and environmental impact and sustainability assessment.

This report provides an overview regarding current LCF technologies and summarizes representative and potential technology pathways. Firstly, in Section 2, the latest scientific and technological progress and technical means of LCF production are described, and normalized flow charts are drawn for each production process. The material and energy balance of the input and output of each production process and the main price constraints at the current scientific and technological level are summarized. The fuel characteristics are summarized and corresponding transport and storage approaches are described in Section 2.3. In Section 3, the leading technical indicators and key data recorded in the current literature are summarized and discussed according to different fuel classifications.

Table 1. Low Carbon Fuels: basic information collected and category overview. Different colors are used to separate the main fuel categories. The technologies are categorized within one of the following four levels of technological maturity: ***Category 1****.* ***Research and development (R&D) phase****. The uncertainty related to price and performance today and in the future is highly significant;* ***Category 2****.* ***Pioneer phase****. The technology has been proven to work through demonstration facilities or semi-commercial plants;* ***Category 3****. Commercial technologies with* ***moderate deployment****. The price and performance of the technology today is well known;* ***Category 4****. Commercial technologies with* ***large deployment****. The price and performance of the technology today is well known and normally only incremental improvements would be expected.*

Category			**Types (by conversion process)**	**Brief Characteristics**		
				Main applications	**Technology status**	**Timeline and current opinion**
Low Carbon Fuels	**Renewable Fuels**	**Biofuels (BtX)**	**Biomass to Liquid (BtL)** Fuels (bioethanol, biodiesel, biomethane)	transportation aviation	Pioneer phase – moderate deployment	2005-, future is uncertain. Biohydrogen and upgraded biomethane were identified as the most promising biofuels, while with limited potential.
			Gaseous (Biogas, Syngas)	transportation	Pioneer phase – moderate deployment	Potential exists, scale matters. A large potential commercial deployment may lead to incremental price reduction.
		Renewable Fuels of Nonbiological Origin (RFNBO)	**Hydrogen** (blue: CCS included; green: produced via electrolysis using renewable electricity)	transportation, maritime, aviation, industry materials	R&D phase – Pioneer phase	Expected large scale 2040-2050. Hydrogen most likely has an important role to play in providing a long-term, low-carbon storage vector.
			Ammonia (blue: CCS included; green: via sustainable electricity)	maritime, transportation	Pioneer phase – moderate deployment	1900-, green ammonia: in the future. Ammonia is still far from being largely recognized as a dominant fuel for power applications. Ammonia's large-scale infrastructure allows it to be deployed in the near future.
			Power to Liquid (PtL) Fuels (e-methanol, e-diesel and e-methane)	maritime, transportation, aviation	R&D phase – Pioneer Phase	2021 use started, large scale expected 2025-2030. Drop-in capability, credible perspective based on large resources of renewable energy.
			Sun to Liquid (StL) Fuels	(expected) aviation transportation	R&D phase – Pioneer Phase	2016 started, expected start to use 2023-2050. Initiate developments essential for the long-term decarbonization of the aviation sector.
	Fuels that can provide GHG savings compared to fossil fuels on a life-cycle basis		**Recycled carbon fuels (RCFs)** from fossil wastes	transportation	Pioneer phase – moderate deployment	2019- Timely transition to the post fossil fuel era, may contribute to the policy objectives of energy diversification and decarbonization of the transport sector.
			Hydrogen from nuclear electricity; Others	transportation	Pioneer phase – moderate deployment	- expected in the future Has great potential with development of nuclear energy

Table 2. LCF matrix: feedstock, technology pathways and fuel types.

	LCF categories	**Input feedstock**	**Technology pathways**	**Fuel type (main products)**	**Technology Status**
Electrification LCFs	Renewable Electricity (RE)	Solar, wind, biomass, hydro	electricity generation	RE	moderate deployment
	Green Hydrogen	Water, RE	Proton exchange membrane electrolysis (PEM)	Hydrogen	pioneer phase
		Water, RE	Alkali electrolysis (AEC)	Hydrogen	moderate deployment
		Water, RE	Solid oxide electrolysis cell (SOEC)	Hydrogen	R&D phase
	Green Ammonia	hydrogen, nitrogen, RE	Haber-hosch (HB)	Ammonia	moderate deployment
	Power to Liquid (PtL)	CO_2, hydrogen, RE	Fischer-Tropsch process (FT PtL)	Gasoline, diesel, kerosene	pioneer phase
		CO_2, hydrogen, RE	Methanol Power-to-Liquid (MeOH PtL)	Gasoline, diesel, kerosene	pioneer phase
Non-electrification LCFs	Biomass to Liquid/Gas (BtX)	organic waste	anaerobic digestion	Biogas (Methane)	pioneer phase
		Biomass	Thermal gasification	Methane, hydrogen	pioneer phase
		Vegetable oil / animal fats	Esterification	Biodiesel (FAME)	moderate deployment
		oil and fats, hydrogen	Hydrotreating	Biodiesel (HVO)	moderate deployment
		dry biomass	Pyrolysis	Bio-oil	pioneer phase
		biomass, water	Hydrothermal liquefaction	Bio-oil	pioneer phase
		biomass, hydrogen	Catalytic hydropyrolysis	Bio-oil	pioneer phase
		cellulosic feedstock	Hydrolysis and Fermentation	Ethanol	R&D phase
		biomass	Thermal gasification and FT process	Biodiesel	R&D phase
		biomass	Syngas compression and methanol synthesis	Methanol	R&D phase
	Sun to Liquid (StL)	Solar, CO_2, CH_4	Solar reforming (SR)	Kerosene	pioneer phase
		Solar, CO_2, CH_4	Solar reforming plus (SR+)	Kerosene	R&D phase
		Solar, CO_2, CH_4	Pure solar thermochemical (ST)	Kerosene	R&D phase
	Blue Hydrogen	Natural gas	Steam methane reforming (SMR) with CCS	Hydrogen	moderate deployment
		Natural gas	Autothermal reforming (ATR) with CCS	Hydrogen	moderate deployment
		Natural gas	Thermal decomposition (NGD) with CCS	Hydrogen	moderate deployment
		Natural gas	Auto-thermal chemical looping reforming (CLRa) with CCS	Hydrogen	pioneer phase
	Pink Hydrogen (nuclear H_2)	Uranium energy, water	Conventional electrolysis (CE)	Hydrogen	pioneer phase
		Uranium energy, water	High temperature electrolysis (THE)	Hydrogen	pioneer phase
		Uranium energy, water	3/4/5 step Cu-Cl cycle	Hydrogen	pioneer phase
	Turquoise Hydrogen	Natural gas	Methane pyrolysis	Hydrogen	R&D phase
	Blue Ammonia	Natural gas	Gas switching reforming (GSR)	Ammonia	moderate deployment
	Recycled Carbon Fuels (RCFs) from fossil wastes	Steel/chemical industry off-gases	Fermentation	Ethanol	pioneer phase
		Steel/chemical industry off-gases	Catalytic synthesis	Methanol	pioneer phase
		waste plastics	Gasification and catalytic synthesis	Methane, diesel	pioneer phase
		waste plastics	Pyrolysis and distillation	Diesel	pioneer phase

2. Technology pathways

This chapter characterizes the different LCF pathways according to according to whether they rely on electricity for production, and outlines the definition of each LCF, current development status, main production methods and processes, as well as future challenges and key development factors in terms of technology pathways.

2.1 Electrification low carbon fuels

2.1.1 Renewable electricity

Renewable electricity is critical to reducing emissions.[1] The decarbonization of energy supply first requires the electrification of heating and transportation. Many low carbon fuels based on electrification have the possibility and potential of large-scale use in the future. Electricity based on renewable energy is the basis of other energy consumption sectors and low-carbon fuel production.

In 2020 at EU level, renewable energy sources accounted for 39% of the electricity and overtook for the first time fossil fuels (36%) as the main power source. In addition, 25% of the electricity came from nuclear power plants. Among renewable sources, the highest share of electricity came from wind turbines (14%), hydropower plants (13%), biofuels (6%) and solar power (5%).[2] Wind power and solar power are also becoming increasingly important in the EU’s renewable electricity market. [3]

Potentials for renewable electricity production, and to some extent transmission lines, represent constraints for production of electrified low-carbon fuels. The power system based on wind, solar, and hydro power is affected by seasonal changes, which is also an essential factor for fuel production. Long-term energy storage may play an important role in reducing costs and increasing capacity in a stable renewable power generation system.[4, 5] The scale effect and location of the variable renewable power system are crucial to the production cost of electricity [6], and also determine the production scale and supply chain transportation cost of the electrification based LCFs.

2.1.2 Green Hydrogen (Hydrogen via electrolysis)

Hydrogen that meets certain sustainability criteria is called green hydrogen. However, there is no international green hydrogen standard yet, and there is no universally recognized definition [7]. At present, green hydrogen used in most literatures is defined as hydrogen produced by using renewable electricity to decompose water into hydrogen and oxygen [8], which is also the definition used in this report. Biomass based renewable energy hydrogen production technology is also classified as green hydrogen in some literature, such as steam reforming of biogas, which is classified here as BtG fuel.

Three water electrolysis methods are investigated: Alkaline Electrolysis Cells (AEC), polymer electrolyte membrane electrolysis cells (PEMECs) or simply polymer electrolyte membrane (PEM) for short, and Solid Oxide Electrolysis Cells (SOEC).

An energy balance for each of the three electrolysis technologies, AEC, PEM and SOEC is shown in Figure 1. For AEC and PEM, the input is 100% electricity while for SOEC electricity is 79.5% of the input energy, while the remaining 20.5% is supplied as thermal energy. This differentiation is done since SOECs operate at higher temperature wherein, the water needs to be converted to steam and the operation occurs at temperatures above 600 °C. [9] The characteristics of input and output streams are presented in Figure 2.

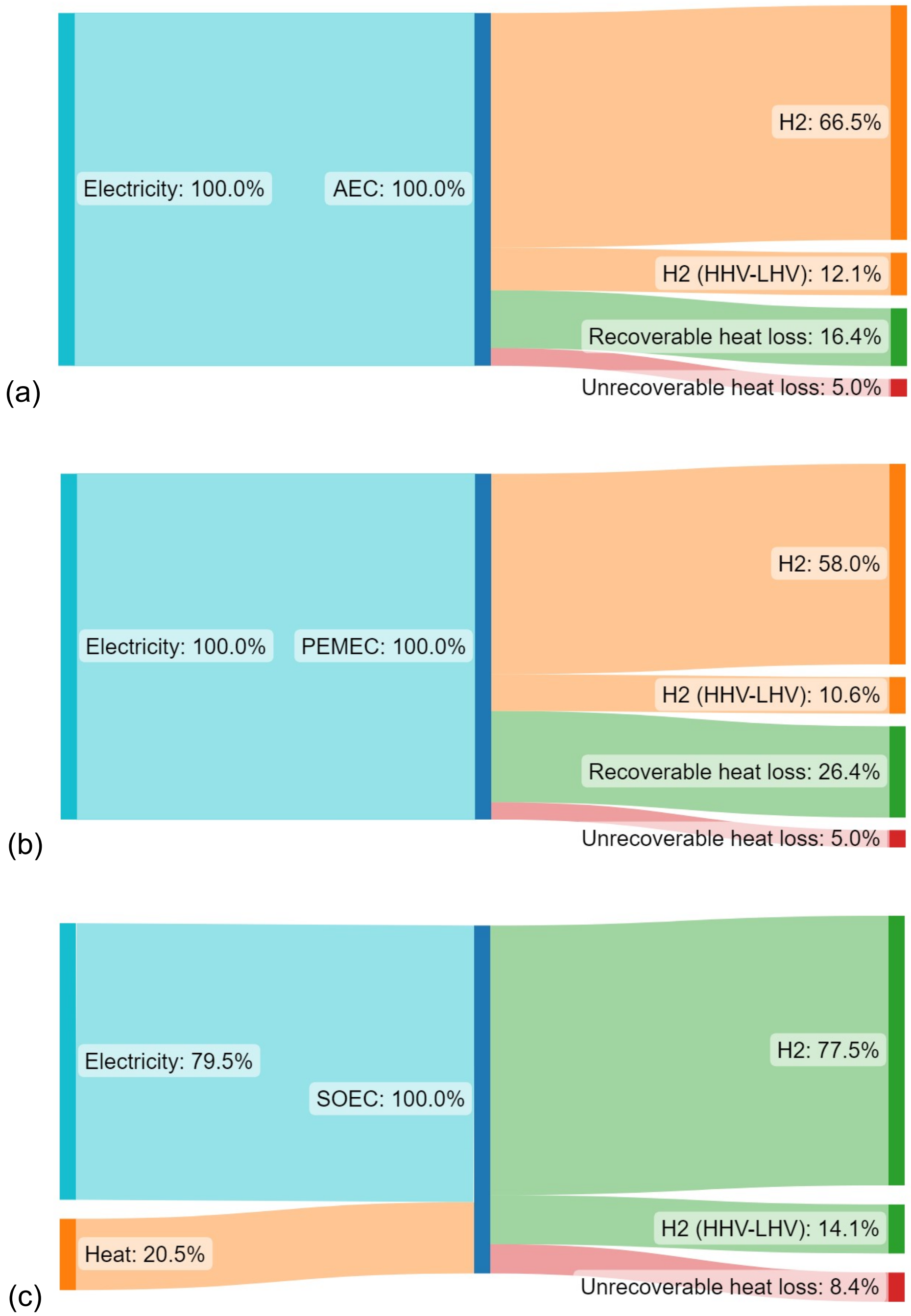


Figure 1. Energy balance (in 2020) for a 1MW (a) alkaline electrolysis cell (operating temperature 20-80℃) (b) polymer electrolyte membrane electrolysis cell (operating temperature 20-200℃) (c) solid oxide electrolysis cell (operating temperature 500-1000℃), compared on LHV basis.(data source: [9][10])

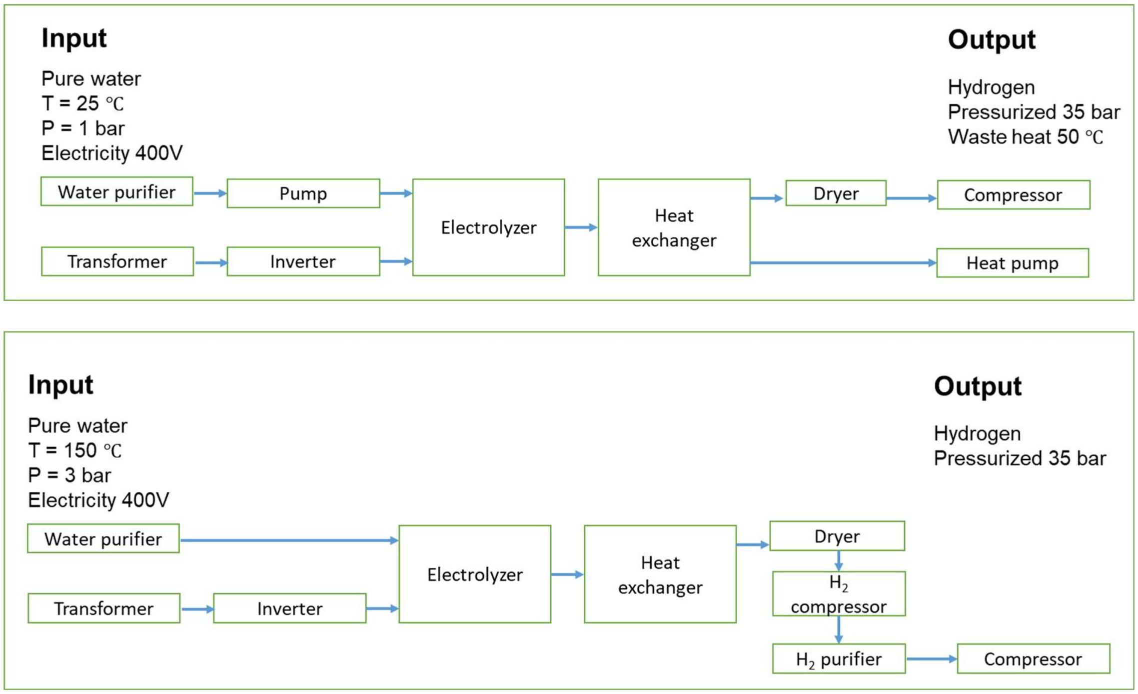


Figure 2. Sketch of electrolysis systems for AEC/PEM (top) and SOEC (bottom). [11, 12]

At present, the cost of green hydrogen based on renewable electricity is about 2-12 USD/kg[8, 13], which is too high to be competitive at present. In 2022, about 1 million tons of hydrogen are produced each year, and gray hydrogen accounts for the vast majority, of which only 1% is blue hydrogen and 0.1% is green hydrogen. The key factors affecting the price of green hydrogen are the cost of electrolysis and the price of renewable electricity used in electrolysis[14]. In the long run, the development of electrolysis technology has a strong potential for future innovation, and reducing the cost of renewable electricity is the key to the large-scale application of green hydrogen.

2.1.3 Green Ammonia

Ammonia is a carbon free carrier with high energy density, with mature transportation network and high flexibility, which can provide a practical next generation system for energy transportation, storage and power generation. [15]

Compared with traditional ammonia plants that produce hydrogen through SMR, the hydrogen input into green ammonia is generated from water electrolysis, and the nitrogen required for ammonia synthesis is produced by an air separation unit (ASU). As shown in Figure 3, the synthesis gas is mixed to the required composition of H_2/N_2 synthetic ammonia using compressor and preheater to increase synthetic air pressure and temperature. In the ammonia converter, the ammonia synthesis is limited by the chemical balance, the unreacted gas is recovered to increase the conversion rate, and the refrigeration cycle is used to separate the synthesis gas from the recovery stream. Therefore, green ammonia is considered as a clean, zero carbon emission fuel.[16]

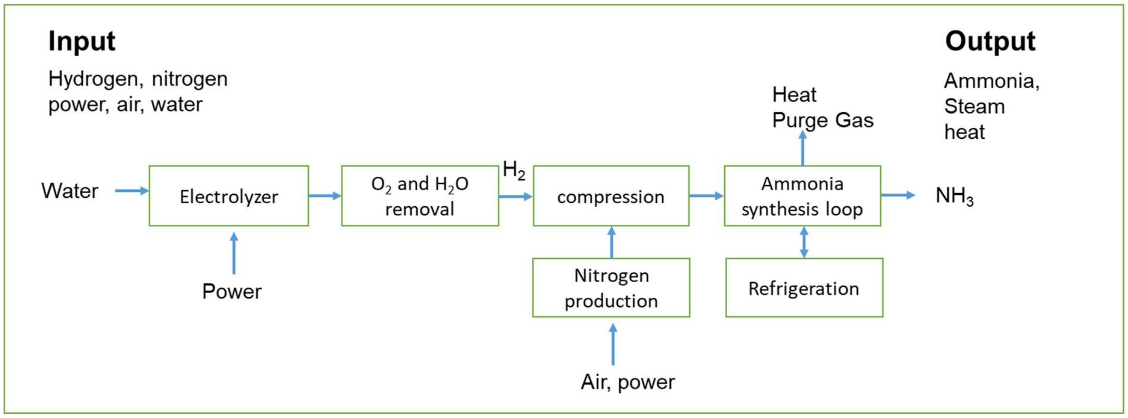


Figure 3. Process flowchart of green ammonia production. (Redrawn from [16])

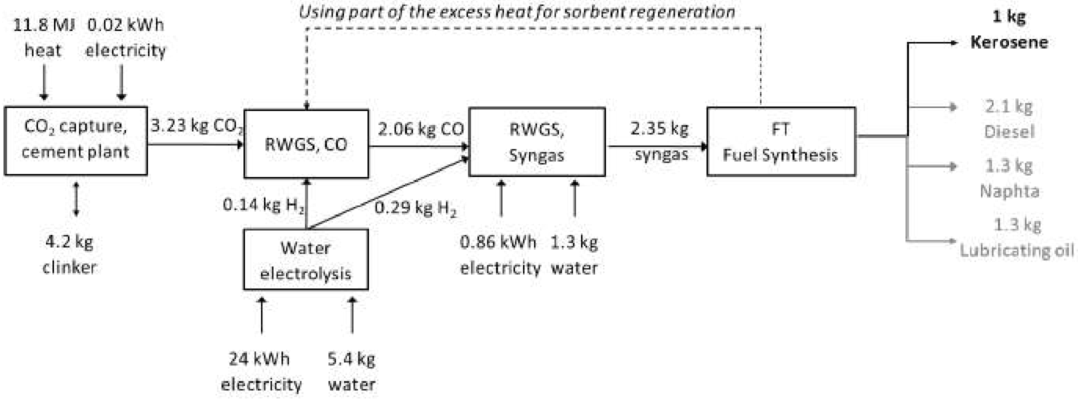
The system inputs are hydrogen, nitrogen and electrical power. For 1L of liquid NH_3 (0.698 kg) or 41.05 mols, 61.575 mols (0.123 kg) H_2 is required. Considering 100% current efficiency, electrical input is equal to the enthalpy change of water dissociation, which is 142 MJ/kg of H_2 or 39.45 kWh for 1 kg of H_2. Taking the practical efficiency of 50%, then the electrolyzer electricity requirement is 9.72 kWh. The production prospect of green ammonia mainly depends on the cost of providing stable electrolytic hydrogen to the ammonia synthesis circuit.[17]

2.1.4 PtX (Power to Liquid/ Gas Fuels)

Power-to-X synthetic liquid fuels or e-fuels are generated via the Fischer-Tropsch process or the methanol route using green hydrogen produced from water electrolysis, renewable electricity and carbon dioxide captured from concentrated sources or from the air directly. The Power to Gas concept is to convert an excess of electricity from renewable energy sources to hydrogen or methane, which is discussed in Section 2.1.2 of green hydrogen and corresponding part of Biomass to methane via thermal gasification, Section 2.2.1.2(5). Therefore, here the two production processes of PtL are introduced, and the main products considered are kerosene and diesel. The standardized unit process is taken from [18].

(1) Fischer-Tropsch process (FT PtL)

The correlation between FT synthesis and PtL and other fuel production routes is based on the fact that syngas can be produced from almost any carbonaceous raw material. In addition to coal, this includes methane (natural gas, flare gas or biogas produced by fermentation) and dry biomass in the gas liquid (GtL) pathway, but also includes synthetic gas produced by CO_2 and hydro chemistry, such as PtL.[19] The FT synthesis of syncrude and subsequent hydrocracking and distillation is adapted for the purpose of this report as shown in the flow diagram.

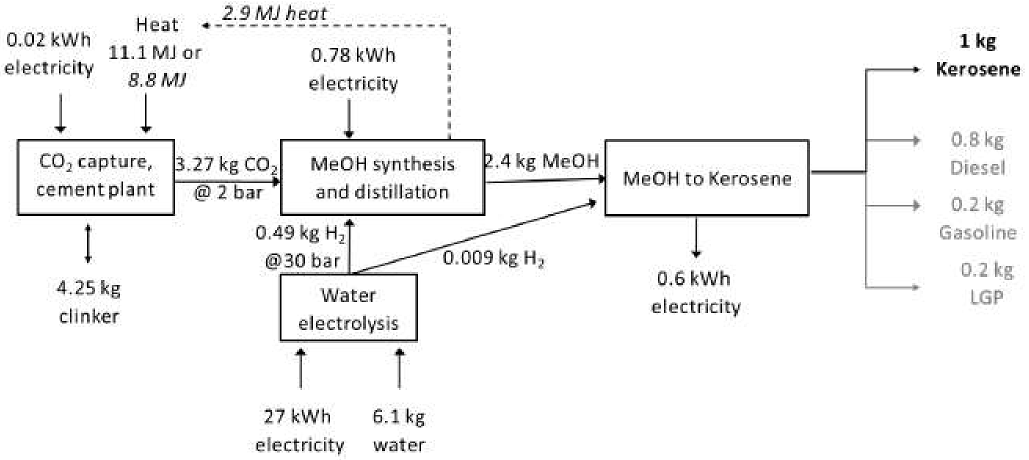


- Green hydrogen demand (55 kWh/kg H_2)
- RWGS: fixed bed reactor; catalyst 57% CuO, 31% ZnO and 11% Al_2O_3; sorbent = zeolite
- FT process: 25 bar; 230; 80% efficiency (20% of energy is converted to heat)
- Average lower heating value FT fuel: 43.2 MJ/kg

Figure 4. Flow diagram of FT PtL pathway [18]

(2) Methanol Power-to-Liquid (MeOH PtL)

An alternative to FT synthesis as liquefaction process is the production of methanol as an intermediate product. Today, methanol is industrially produced from synthesis gas, typically generated from natural gas or coal, using the ternary Cu-ZnO-Al_2O_3 catalyst. Methanol is normally not used directly as fuel, but is converted to gasoline or kerosene for direct applications.



- Green hydrogen demand (55 kWh/kgH_2)
- Catalyst CuO/Al_2O_3/ZnO
- Integration of MeOH conversion and CO_2 capture leads to 33% energy savings in heat input
- 2.42 kg MeOH/MJ fuel mixture

Figure 5. Flow diagram of MeOH PtL pathway [18]

2.2 Non-electrification low carbon fuels

2.2.1 BtX (Biomass to Liquid/Gas Fuels)

2.2.1.1 Biomass to gases

Biogas plants produce methane rich gases based on biodegradable organic materials. Raw materials are transported to the factory by road or pipeline. In the factory, the feedstock undergoes an anaerobic process to produce biogas. Biogas can be directly used for natural gas engines, local cogeneration, local gas-fired boilers, or upgraded to biological SNG (synthetic natural gas) as shown in Figure 6 and 7.

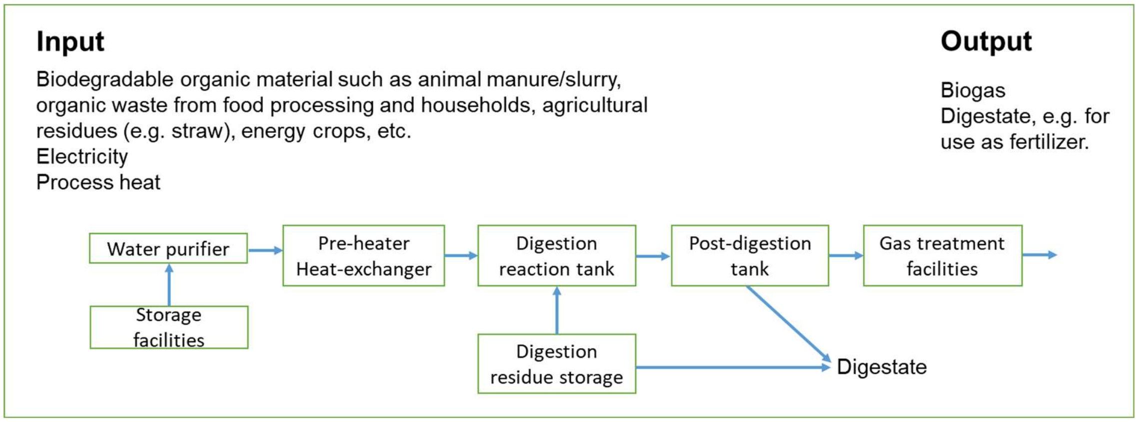


Figure 6. Typical components and flows in an anaerobic digestion biogas plant [9]

Figure 7. Biomass gasification process to bio-SNG [9]

After gasification, it can be upgraded through gas purification, CO_2 removal, drying and synthesis gas methanation to achieve the methane content of about 95-98% required for compatibility with the gas in the natural gas grid.[20]

The methanation process can be catalyzed by converting syngas into methane and water. Because the methanation process generates heat, it is usually an advantage to integrate the gasification and methanation processes in one unit. Methanation can also be carried out through biological processes. The methanation process can theoretically achieve 80% efficiency, and the rest of the energy content in the feedstock can be converted into heat. Practically, the overall efficiency from solid fuel to bio-SNG ranges between 50% and 60% at present.

2.2.1.2 Biomass to liquid

(1) Vegetable oil, used cooking oil and animal fat based biodiesel

Fatty acid methyl ester (FAME), also known as biodiesel, can be produced from vegetable oils such as rapeseed oil and soybean oil, used cooking oil (UCO) and recycled animal fat, as shown in Figure 8.

The primary inputs to the production process are the vegetable oil or UCO/animal fats, methanol, electricity, some thermal energy, the catalyst, and some acids and bases to treat the feedstocks and finished products. The process produces FAME, glycerine, and in some cases potassium salts that can be sold as fertilizer.

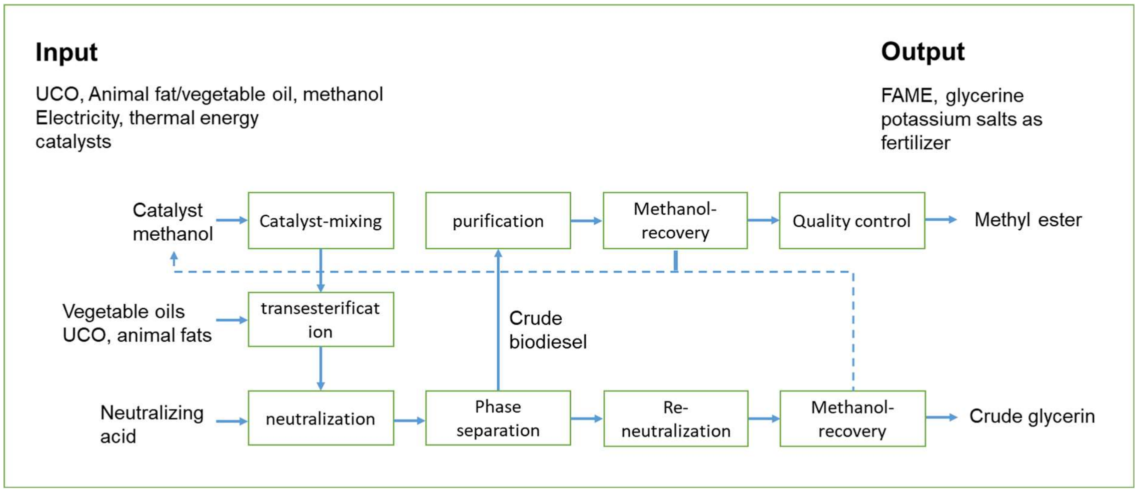


Figure 8. FAME/Biodiesel production process based on vegetable and animal oil [21]

(2) Hydrogenated vegetable oil / renewable diesel

Hydrogenated vegetable oil (HVO) is also known as renewable diesel. The HVO unit uses the same raw materials as the FAME unit, including used edible oil and animal fat. However, the raw materials do not react with methanol, but with hydrogen in the presence of catalyst. Its operating temperature and pressure are higher than those of a FAME unit.

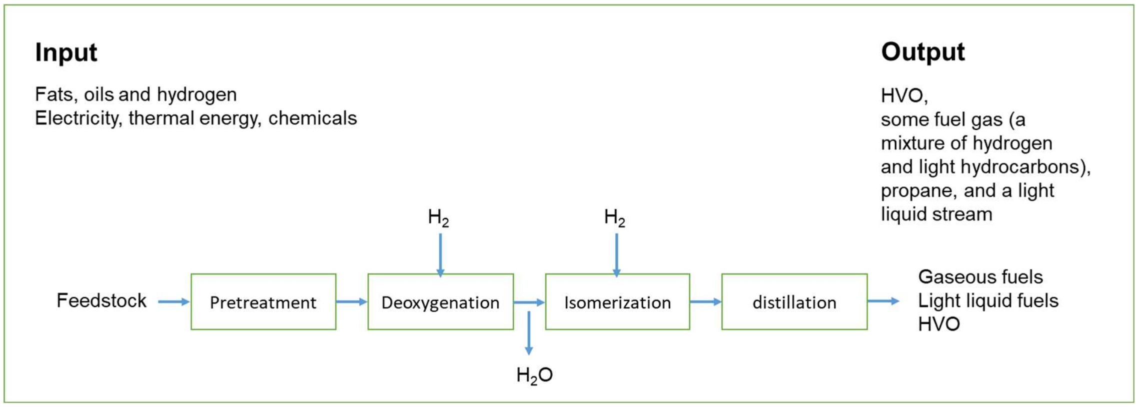


Figure 9. HVO production process [9]

(3) Bio-oil via pyrolysis, hydrothermal liquefaction and catalytic hydropyrolysis

Biomass pyrolysis products include biochar, bio oil and gas, including methane, hydrogen, carbon monoxide and carbon dioxide. A wide range of biomass raw materials can be used in the pyrolysis process, but the moisture content of the raw materials should be rather low. Fast pyrolysis is the most widely used pyrolysis system at present for production of energy carriers, which can be carried out in relatively small scale and remote locations, which improves the energy density of biomass resources and reduces the transportation and processing costs.

Pyrolysis provides a flexible and attractive way to convert solid biomass into liquid fuel that is easy to store and transport, and can be successfully used to produce heat, electricity and chemicals.

Hydrothermal liquefaction of biomass is to transform biomass thermochemically into liquid fuel by treating it in pressurized water environment for enough time to decompose solid biomass structure into main liquid components. Typical hydrothermal treatment conditions are 250 – 420 °C and 40 to 350 bar. Alkali catalysts are usually used to promote the degradation of macromolecules and inhibit the formation of tar, char and coke through hydrolysis, decarboxylation and depolymerization type reactions. This process can handle most types of biomass and does not require dry biomass.

Catalytic hydropyrolysis (CHyP) of biomass is to convert biomass thermochemically into bio oil or liquid fuel by treating it with hydrogen and catalyst, so as to decompose the structure of solid biomass into liquid, gas and solid components. Typical catalytic hydropyrolysis process conditions are 375-475 °C and 10-30 bar operating pressure. The catalytic hydropyrolysis stage is followed by a further hydrotreating stage, and can produce liquid fuels within the range of gasoline and diesel instead of bio oil. As with the fast pyrolysis process, the feedstock must be properly sized and relatively dry.

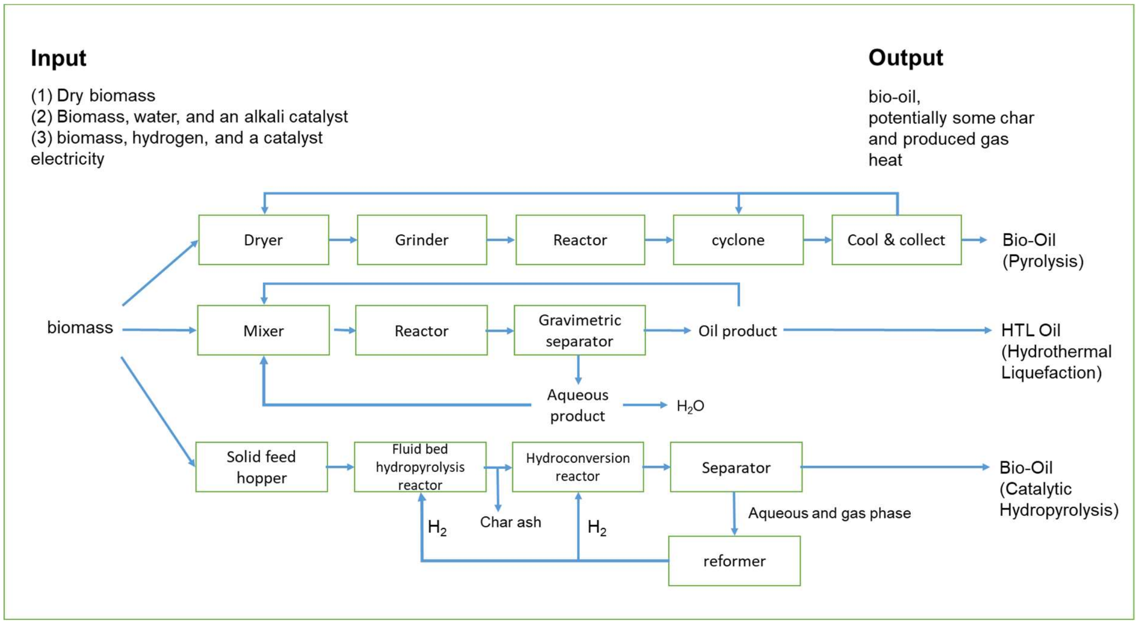


Figure 10. Bio-oil production process via pyrolysis, hydrothermal liquefaction and catalytic hydropyrolysis [9, 22, 23]

(4) Cellulosic Ethanol

Cellulose is an important component of the primary cell wall of green plants. Cellulose raw materials (can be straw, corn straw, bagasse or wood residue) usually go through the pretreatment stage to separate the cellulose part of the material from lignin and make the raw materials easy to hydrolyze. Acid and/or steam can be used in the pre-treatment phase to achieve this goal. In the hydrolysis stage, cellulose molecules are decomposed into smaller polysaccharides or glucose units. Hydrolysis can be carried out with cellulase or acid. Most process developers use enzymes. After the hydrolysis phase, yeast is added to convert sugar into ethanol and carbon dioxide.

The main inputs are cellulose raw materials, water and chemicals or enzymes used in the process. The quantity and type of raw materials vary depending on the process developer. The output is ethanol and electricity.[24]

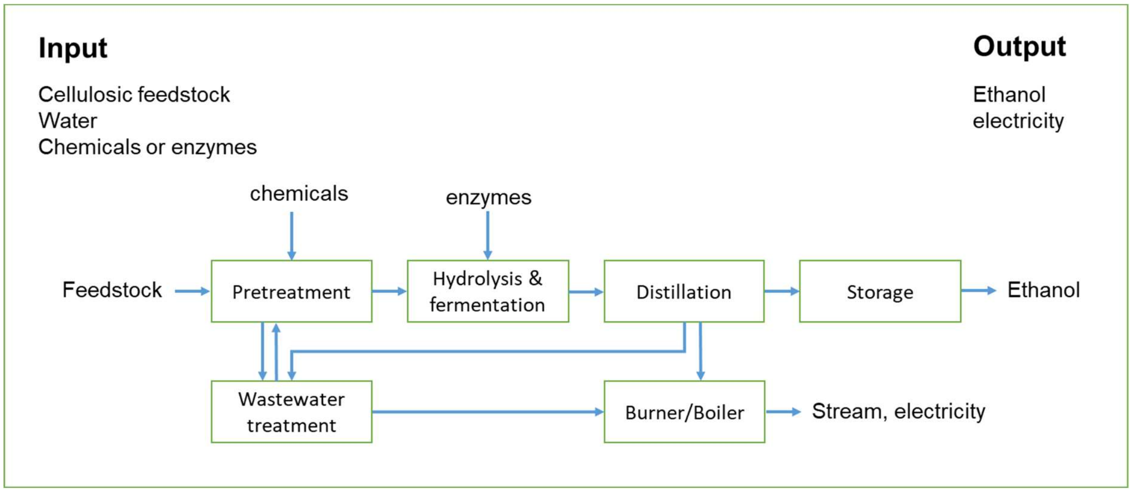


Figure 11. Cellulosic ethanol production process [25]

(5) Renewable diesel and jet fuel from biomass gasification and FT

Producing diesel or jet fuel from biomass is a two-step process. The first step is to convert solid biomass into gas phase, and the second step is to convert gas into liquid fuel. Gasification is a process of converting organic or fossil based carbonaceous materials into carbon monoxide, hydrogen and carbon dioxide (synthesis gas) at high temperature (>700°C), without combustion and with controlled oxygen and/or steam content. Then carbon monoxide reacts with water through water gas shift reaction to form carbon dioxide and more hydrogen. The Fischer Tropsch process converts the mixture of carbon monoxide gas and hydrogen into liquid hydrocarbons. The input biomass can be agricultural or forestry residues.

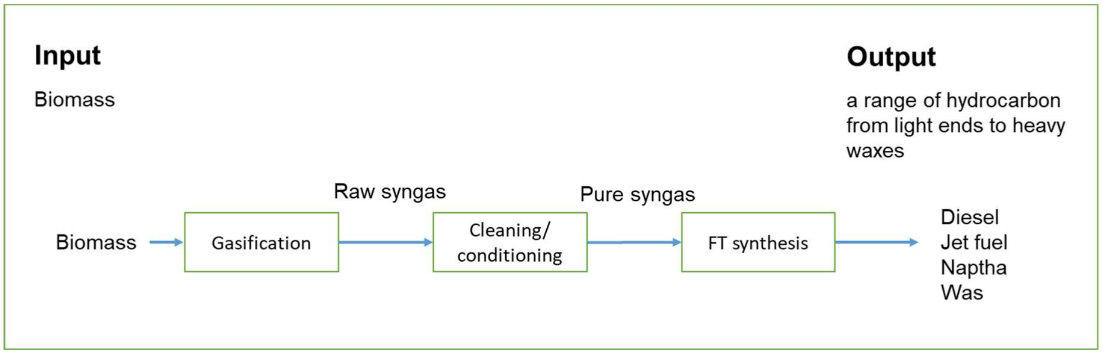


Figure 12. Biomass to diesel and jet production process [9]

(6) Methanol from biomass gasification

The front end of this process is the same as the gasification process described previously. Methanol production from biomass is a two-step process. In the first step, solid biomass is converted into biosynthetic gas, and in the second step, the synthetic gas is further converted into methanol.

The stoichiometry of synthesis gas methanol production requires that the ratio of H_2/CO is equal to 2. Through reverse water gas shift reaction, the H_2/CO ratio can be reduced to a certain extent. The methanol synthesis reaction is usually carried out at about 40 to 120 bar and 200 to 300°C. Dimethyl ether (DME) can also be produced in other process steps instead of methanol. Methanol can also be further processed into gasoline.

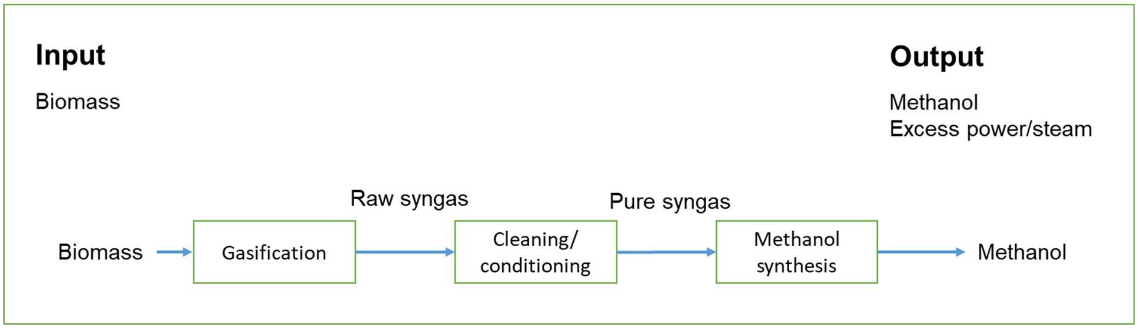


Figure 13. Biomass to methanol production process [20]

2.2.2 StL (Sun to Liquid Fuels)

The Sun-to-Liquid pathways described and modelled in the following are the technologies developed by Synhelion. They are based on using CO_2 and water combined with high-temperature heat generated via a solar concentrating plant. Heat is stored so that continuous fuel production will be possible.[18]

The Synhelion plant is the solar part in the Sun-to-Liquid pathway. It provides the process heat to start the chemical reaction to produce syngas. Synhelion is planning to reach a production volume of 700’000 t/a fuel by 2030 while entering the market within two years. This volume would cover roughly half of the kerosene used for Swiss civil aircraft or 15% of the Swiss diesel and gasoline use.[18] In order to ensure a constant supply of process heat to the industrial processes, the Synhelion plants will be equipped with thermal energy storage and be located at sites with high solar irradiation.

Three configurations are currently designed: Solar reforming, Solar reforming plus, and Pure thermochemical reaction. All three production pathways include the conversion of CO_2, H_2O (and CH_4) to syngas with the input of solar process heat supplied by solar concentrators.

(1) Solar reforming (SR)

Within this process, methane (from natural gas or biogas) is combined with CO_2, water and solar energy to produce syngas (CO and H_2). The reforming catalyst is a mixture of Fe, C, Cr, Ni, Nb, Ti. The resulting syngas is converted to syncrude through conventional Fischer-Tropsch synthesis, i.e. through the reaction of the syngas with the input of heat, electricity, and water.

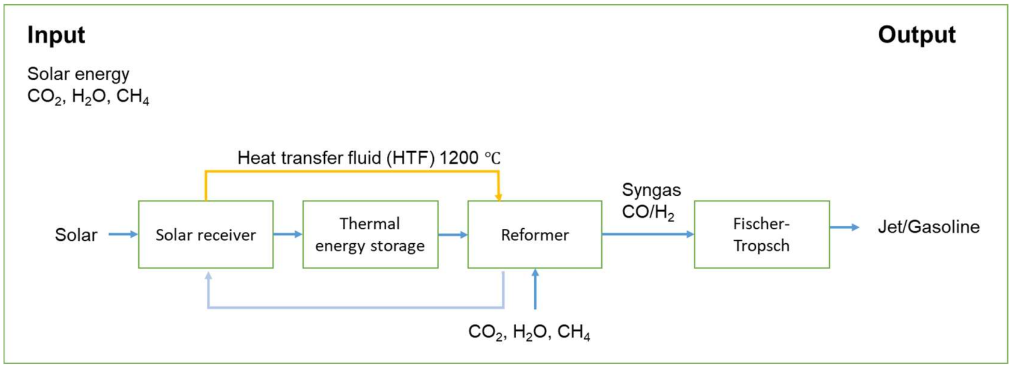


Figure 14. Design of a Synhelion solar reforming syncrude production pathway. High-temperature solar reforming of CH_4 takes place together with its reaction with CO_2 and H_2O to produce syngas. [18]

(2) Solar reforming plus (SR+)

A process called "solar reforming plus" is developed by Synhelion, where part of the required hydrogen is produced in an electrolyser powered by a concentrated solar power plant. A reverse water gas shift process is combined with the Fischer-Tropsch synthesis to produce syncrude. Due to the significant reduction of required CH_4 input, the share of renewable carbon increases to 70%-100%. Again, the required CH_4 input may be covered with either natural gas or biogas. However, in this case, the required CH_4 input is reduced compared to the required CO_2, so the CO_2 content in the biogas is not high enough to cover the CO_2 amount. The biogas input is thus calculated according to the required CH_4 amount, and the contained CO_2 contributes to a reduction of external CO_2 supply.

(3) Pure solar thermochemical (ST)

In the pure solar thermochemical pathway, the Synhelion plant is used to produce syngas from CO_2 and H_2O only in a two-step redox process, without adding methane and thus without fossil feedstock. The share of renewable carbon may thus be 100%. The syncrude is produced through conventional Fischer-Tropsch synthesis. This production pathway is under development and may reach larger scales by 2030.

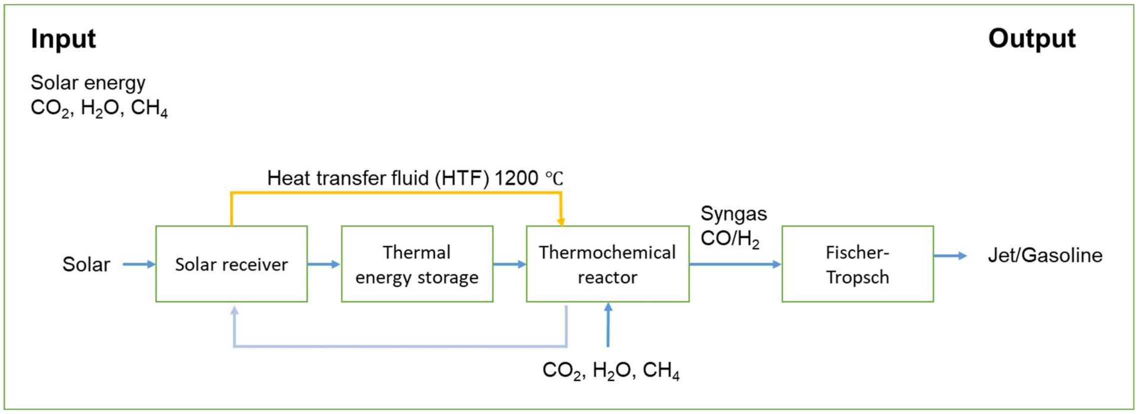


Figure 15. A Synhelion pure thermochemical syncrude production pathway [18]

2.2.3 Blue hydrogen

Blue hydrogen refers to hydrogen produced by reducing carbon emissions in the life cycle based on the traditional hydrogen production based on natural gas combined with carbon capture and storage technology, including some new low-carbon production technologies.

(1) SMR-CCS

Steam methane reforming is a mature hydrogen production method. The process flow diagram (Figure 16) shows that in the reforming reactor, natural gas reacts with steam under high pressure to generate synthesis gas. The reaction is carried out in the presence of nickel based catalyst to produce carbon monoxide and hydrogen rich synthesis gas. The syngas is cooled and sent to the Water Gas Shift (WGS) reactor, where carbon monoxide is converted into carbon dioxide and hydrogen by adding steam. The hydrogen generated is purified in the synthesis gas purification unit. It is then pressurized and stored in a tank. CO_2 emissions from the syngas purification unit are compressed and piped to the carbon storage unit. [26]

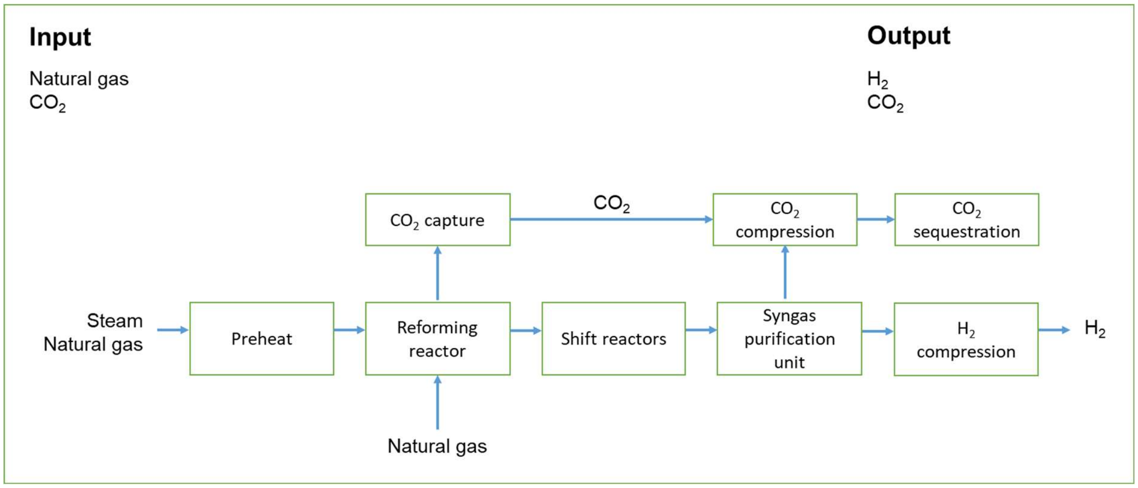


Figure 16. Process flow diagram of steam methane reforming with carbon capture and storage (SMR-CCS). [26]

(2) ATR-CCS

The process flow diagram in Figure 17 shows the autothermal reactor, water-gas shift reactor, synthesis gas purification, CO_2 compression, transportation, storage, hydrogen storage and air separation unit (ASU). Oxygen (generated in ASU), steam and methane react on nickel catalyst in ATR reactor to generate synthesis gas, which is cooled to the temperature required for water gas shift reaction. The transformed gas is sent to the synthesis gas for purification, where carbon dioxide is separated from the hydrogen rich gas. The separated carbon dioxide is compressed and stored, while the gas rich in hydrogen (including unconverted carbon dioxide, argon and some trace gases) is sent to the pressure swing adsorption unit (PSA). In PSA, it is assumed that 90% hydrogen is recovered with 99.9% purity, and the remaining gas (fuel gas) is used as fuel in the boiler/furnace. [26]

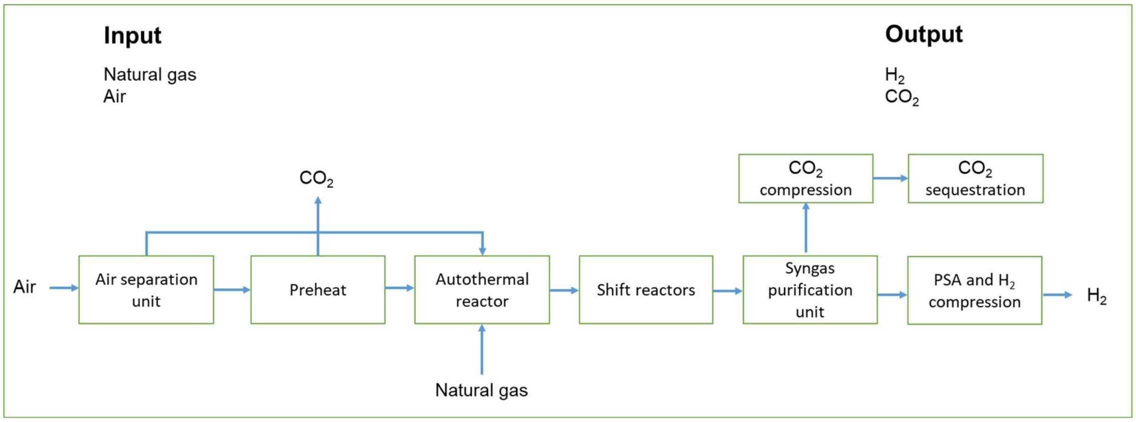


Figure 17. Process flow diagram of autothermal reforming with a carbon capture and storage (ATR-CCS) plant.[26]

(3) NGD-CCS

Figure 18 shows the flow chart defining the scope and boundary of the NGD approach modeling. Natural gas is sent to a thermal decomposition unit and decomposed into hydrogen and carbon. The thermal decomposition reaction is endothermic. Without the catalyst, the reaction requires a high temperature (above 1000°C) to achieve a reasonable reaction rate. Generally, an iron ore catalyst is used. When the carbon is removed, the hydrogen and natural gas leaving the cyclone separator and filter are pressurized and cooled to the ambient temperature before entering the PSA unit, and the unconverted natural gas in the PSA unit is captured to generate pure hydrogen. In PSA, it is assumed that 90% hydrogen is recovered with 99.9% purity, and the remaining gas is recycled to the fluidized bed reactor. The heat required for the thermal decomposition process is provided by burning natural gas. Carbon capture units capture CO_2 emissions from natural gas combustion. The captured CO_2 is then transported and stored underground.[26]

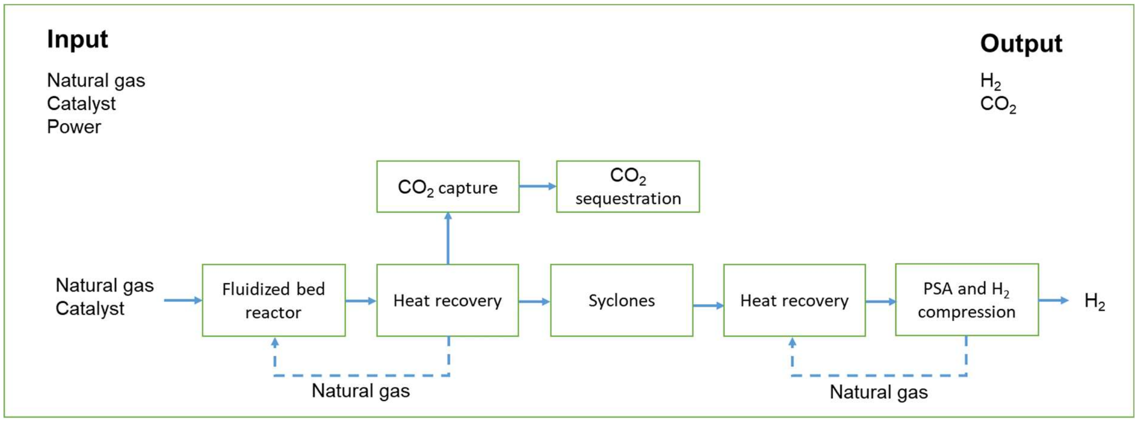


Figure 18. Process flow diagram of the thermal decomposition of natural gas in a carbon capture and storage (NGD-CCS) plant. [26]

(4) Auto-thermal Chemical Looping Reforming (CLRa)

One of the most promising technologies for producing hydrogen from gaseous fuels with the reduction of CO_2 emissions is auto-thermal Chemical Looping Reforming (CLRa). The CLRa process is based on partial oxidation of the fuel or the combustion of a fraction of the fuel utilizing an oxygen carrier material that transfers the necessary oxygen from air to the fuel, but avoiding that both compounds are in direct contact. This oxygen carrier is based on a metal oxide, M_xO_y, which is continuously circulating between two interconnected fluidized bed reactors. On the one hand, this process does not require burning part of the natural gas or the tail gas from the PSA unit in separate equipment as in an SMR system, with the consequent generation of CO_2 emissions to provide the necessary heat for the endothermic reforming reactions. On the other hand, an ASU is not necessary to carry out the partial combustion of methane with pure oxygen as in the POX and ATR processes. [27]

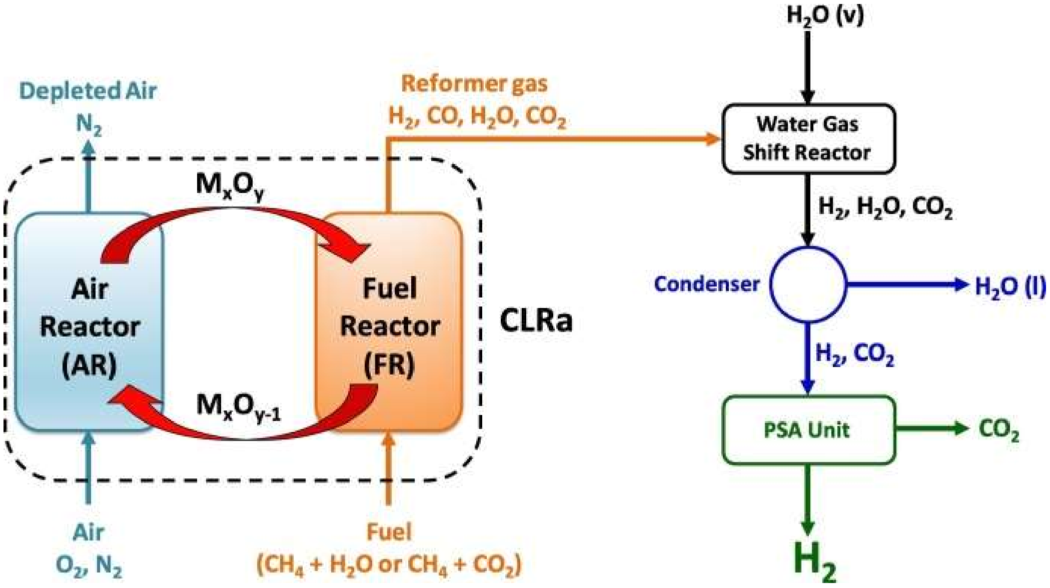


Figure 19. Auto-thermal Chemical Looping Reforming (CLRa) scheme for hydrogen production. [27]

2.2.4 Pink hydrogen (Nuclear based H_2)

The generated electrical and thermal energy in nuclear power plants (NPPs) are employed in the production processes of hydrogen.

(1) Conventional electrolysis (CE)

Electrolytic water splitting is a traditional hydrogen production technology. By decomposing water into hydrogen and oxygen, direct current (DC) is used to control the power balance. Then, electrons flow from the negative pole of the DC power supply to the cathode, where hydrogen ions consume electrons to form hydrogen. [28]

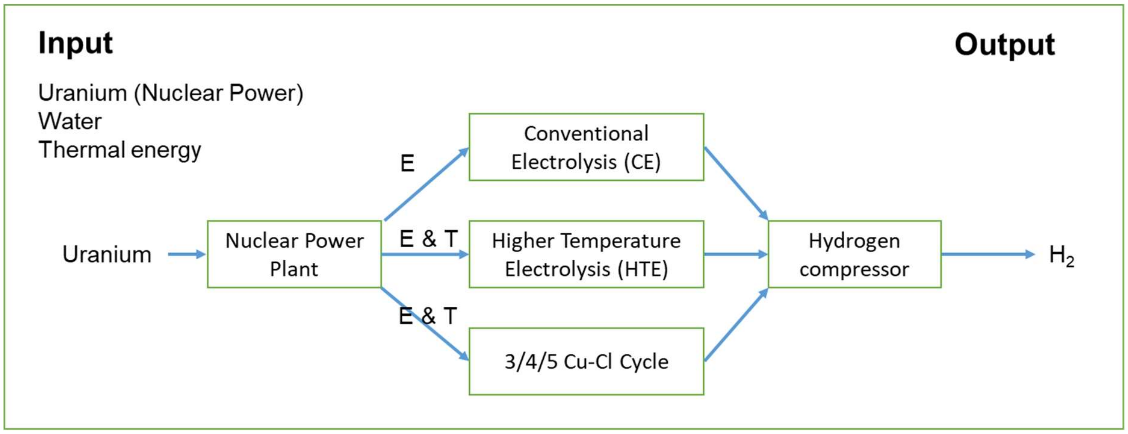


Figure 20. Nuclear-based hydrogen production methods' system layout. E: electricity, T: Thermal energy [28]

(2) High temperature electrolysis (HTE)

Unlike conventional electrolysis methods, nuclear HTE utilizes the heat from the NPP to mitigate consumed electricity for electrolysis. Operating temperatures, electrolyte properties, and pressures create the differences between the electrolysis methods. Electrolysis of water via HTE occurs at 1100–1250 K. As an electrolyte, yttria-stabilized zirconia is utilized in general for this process [20].

(3) Copper–chlorine (Cu–Cl) cycles

Cu–Cl cycles operate a sequence of reactions to split water into hydrogen and oxygen. The five step copper-chlorine cycle splits water by employing copper chloride compounds. The copper is generated electrolytically in the cycle, and then transferred to a thermochemical hydrogen reactor operating exothermically. Lastly, the produced copper reacts with HCl gas to generate hydrogen gas and molten Cu–Cl.

The four step copper-chlorine cycle unifies step 2 and step 3 in Table 2 to remove the intermediate production and handling of copper solids [21]. The three-step Cu–Cl cycle combines the hydrogen production step and the combined step in 4 step Cu–Cl cycle by directly supplying aqueous Cu chloride to the hydrolysis chamber. Due to combining these two steps, 4 step Cu–Cl cycle requires lower thermal energy input but higher electrical energy input than the 5-step Cu–Cl cycle since the production of hydrogen and aqueous Cu chloride is achieved through a CuCl\HCl electrolyzer.

Table 3. Inputs and outputs of the nuclear-based hydrogen production methods [28]

Nuclear-based hydrogen production method	Input			Output	
	Electricity, nuclear (MJ)	Heat, nuclear (MJ)	Water (kg)	H_2	O_2
CE	**192.6**	**–**	**9**	**1**	**8**
HTE	**104.04**	**24.01**	**9**	**1**	**8**
3 step Cu–Cl	**67.15**	**325**	**9**	**1**	**8**
4 step Cu–Cl	**67.15**	**289.9**	**9**	**1**	**8**
5 step Cu–Cl	**50.3**	**352.26**	**9**	**1**	**8**

2.2.5 Turquoise hydrogen (Methane pyrolysis based H_2)

Another alternative production of low-carbon hydrogen is methane pyrolysis, in which CH_4 is decomposed into solid carbon and H_2. Methane pyrolysis can be used as a bridge technology until cheap renewable electricity is available, while deploying infrastructure and end use applications[29]. Before the establishment of renewable energy, it can be a suitable temporary solution. The decomposition of methane has been extensively studied on metals (nickel, cobalt, iron) and carbon catalysts. From an industrial perspective, only the use of iron and carbon catalysts is feasible and non-toxic. However, it requires harsh temperature and further scientific and technological development to obtain higher hydrogen yield than iron and carbon catalysts.[30]

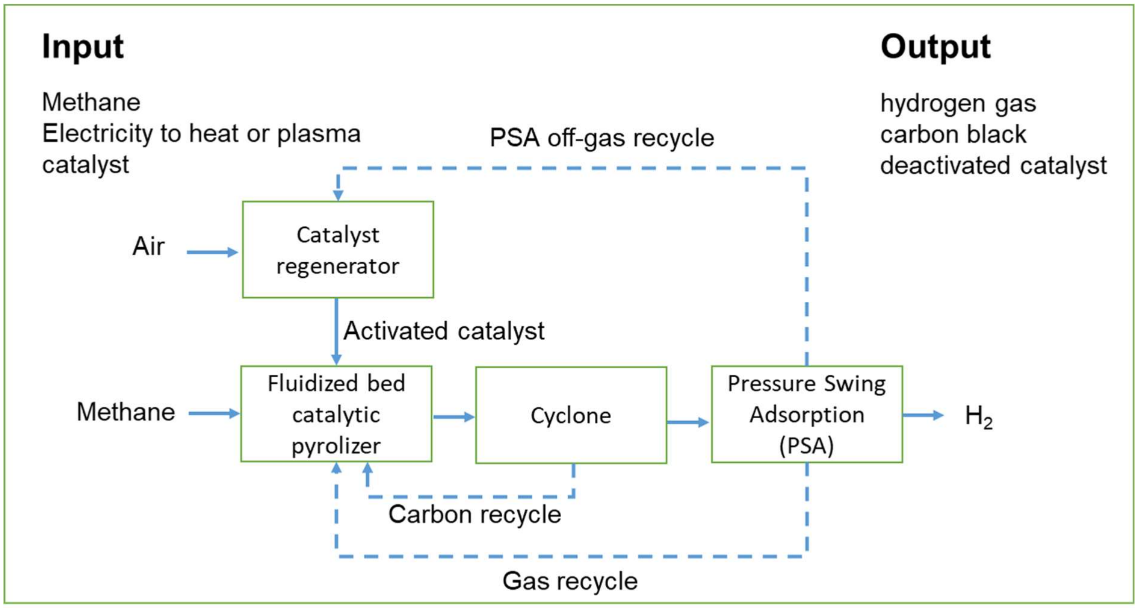


Figure 21. Block flow diagram of hydrogen production by methane pyrolysis, Fluidized bed catalytic-assisted decomposition [30]

2.2.6 Blue ammonia

The process shown in Figure 22 is a typical blue ammonia production process with CCS, with a combustion tube reformer (FTR) and an autothermal reformer (ATR), in which the required

N_2 is provided through the combustion of synthesis gas and air. The two-step absolute hot water gas shift (WGS) series maximizes the production of H_2, followed by the CO_2 removal step to generate pure CO_2 flow for utilization or storage.[17]

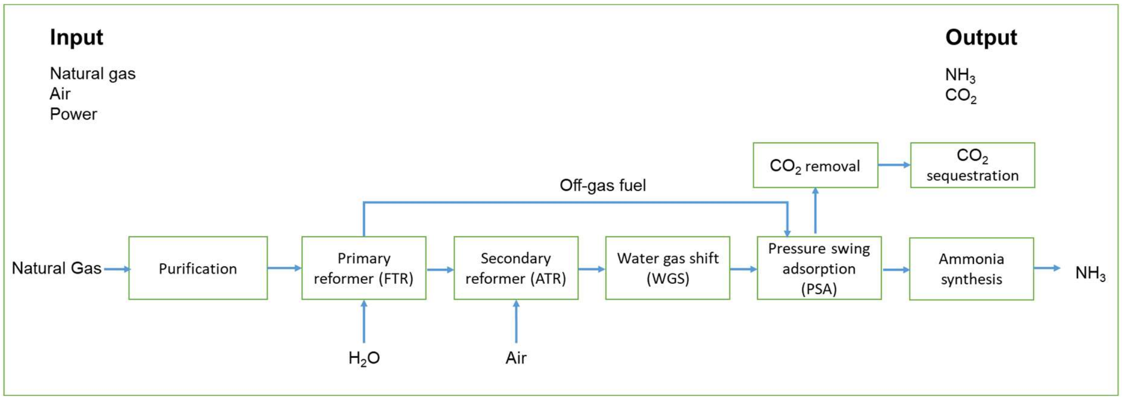


Figure 22. Flow diagram of blue ammonia production process [17]

2.2.7 Recycled carbon fuels from fossil waste resources

Recycled carbon fuels (RCFs) are fuels produced from fossil wastes that cannot be avoided, reused or recycled and have the potential to reduce GHG emissions relative to conventional transport fuels. Feedstock include industrial waste gases and the fossil-derived fraction of municipal solid waste (e.g. non-recyclable plastic). Some feedstock can be considered part renewable and part RCF when combined with biogenic material such as food waste. The two main feedstock considered here are steel/chemical industry off-gases, and waste plastics. [31]

2.3 Transport and storage technologies

In Section 2.1 and 2.2, various fuel production pathways are presented. This Section gives an overview of the perspective of fuel types. Table 4 summarizes the physical properties of fuels discussed, which determine their most suitable transport and storage methods.

Table 4. Comparison of different fuel properties, sorted by higher heating value [32][33]

Fuel	**Boiling point (°C)**	**Energy density (kWh/L)**	**Lower heating value (LHV, kWh/kg)**	**Higher heating value (HHV, kWh/kg)**
Ammonia	-33.34	3.53	5.22	6.25
Methanol	64.7	4.67	5.6	6.4
Ethanol	78.4	6.3	7.4	8.2
Bio-oil	Decomposes	9.2	11.1	11.8
Kerosene	150-300	10.7	11.9	12.7
Diesel	163-357	10.7	11.9	12.7
Synthetic gasoline	69–200	9.7	12.2	13.0
Methane	-161.6	0.010	12.7	14.75
Liquid hydrogen	−252.9	2.5	33.3	39.4

2.3.1 Hydrogen

Hydrogen transportation shall be divided into long-distance and short-distance distribution of the last mile. The quantity to be delivered and the transportation distance determines the most appropriate hydrogen transportation mode. The main modes of hydrogen transportation are trucks or trailers, ships, pipelines or railways. Trucks are used for road transportation, with a distance of up to 4000 km, while trailers (trucks loaded with multiple long cylinders of gaseous compressed hydrogen) can only travel for a long distance. Railways and ships are used for long-distance transportation of more than 2000 km. The hydrogen in the pipeline is most suitable for transportation under high pressure for medium and long distances, but it may also exist under low pressure for short distance. Compressed gas shall be transported by high-pressure cylinder, pipeline trailer or pipeline. Liquid hydrogen is transported in special double-wall insulated tanks to prevent the evaporation of liquid hydrogen. Metal hydride can be used for transportation by absorbing hydrogen with metal hydride and then loading the entire container onto a trailer or rail car for transportation to the required location. The transportation of ammonia is well known; however, the use of ammonia as a hydrogen transport medium does not represent a common choice today. Transport vehicles and vehicles vary in capacity, flexibility, cost, land demand, etc. [10]

Figure 23 illustrated the hydrogen delivery cost with distance. For low electricity prices, hydrogen pipeline is the cheapest option, with a maximum length of 6500 km. Later, LH_2 becomes a more economical option. From about 10,000 km, LOHC has become the most cost competitive. For very long distances (more than 15,000 km), the performance of chemical carriers (ammonia and LOHC) is superior to LH_2, mainly due to evaporation. If there is no pipeline, it is the cheapest to transport compressed hydrogen, up to 3000 kilometers long.

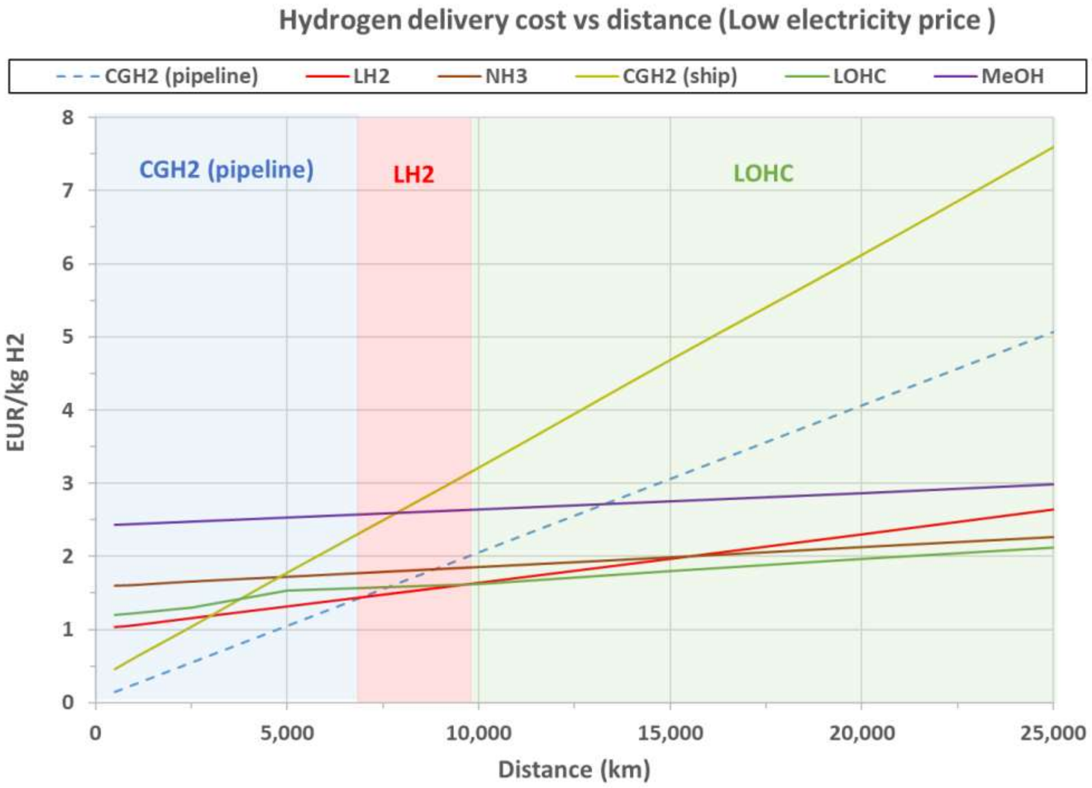


Figure 23. Hydrogen delivery costs plotted against distance for 1 Mt H_2/year and low electricity price. [34]

Hydrogen is expected to be the power storage option for long-term energy storage. Large scale compressed gaseous hydrogen storage includes three modes: storage vessels, geological storage and other underground storage technologies. Storage vessels for high-pressure hydrogen gas have three types: stationary, vehicular, and bulk transportation. There are five types of geological storage: depleted natural gas & oil reservoirs, aquifers, salt caverns, abandoned mines, and rock caverns. [35] Hydrogen storage cost significantly impacts the hydrogen production cost. [26]

2.3.2 Ammonia

Large amounts of ammonia are usually stored and transported in a completely refrigerated state at a temperature of -33°C, such as ocean transportation by ship. The non-refrigerated ammonia is stored in a pressurized thermal stress relief container according to the change of ambient temperature, and the maximum storage capacity is limited to several hundred tons. The capacity of some refrigerated ball storage systems is between 500 and 3000 tons. For anhydrous ammonia, the transfer process operation on ship and shore is the main source of risk factors. A large amount of other non-refrigerated ammonia is distributed by railway and road tankers, thus involving the operation of pressure vessels during assembly. [16] The estimated capital costs for ammonia energy storage is between 1350 and 1590 CHF/kW. [32] Existing vast infrastructure stores and distributes the global deployment of ammonia across the globe. This mature distribution stems from the widespread use of ammonia in the fertilization industry, with a well-established international maritime trade network, with an extensive chain of ports that can handle ammonia on a large scale. [15]

2.3.3 Hydrocarbons

The other LCFs are hydrocarbons, including Diesel, Kerosene, Gasoline that may be transported as liquids in mixtures or as separate purity products in pipelines, rail cars, trucks, ships, and barges. In addition, biodiesel and some biomass fuels will be degraded due to oxidation, contact with water and/or microbial activities, which are also factors that need special consideration during transportation and storage.[36]

3. Technology indicators

This section provides an overview of technology data for each fuel production pathway, including technology readiness level for general LCFs and jet fuels, cost indicators and process efficiency.

3.1 Technology readiness level (TRL)

As listed in Table 5, the TRL of LCF technologies are summarized. Although the TRLs of some fuel production technologies have reached the level of complete systems and practical industrial applications (8-9), most TRLs are at the stage where key technologies are available in the industrial environment or technology practices are obtained in practical applications (5-7). A few emerging fuel technologies, such as StL and some BtL, and turquoise hydrogen, are still in the laboratory prototype and theoretical feasible stage (3-5) and have great development potential in the future. To sum up, most of the current literature has given the TRL of the corresponding technology from the perspective of technological development, but the data on the feasibility of economic and industrial scale are relatively lacking. In particular, there is a lack of good evaluation indicators for the future development of emerging technologies.

Table 6 lists the TRL of low carbon jet fuels, which will be analyzed separately as the aviation sector.

Table 5. Current TRL of LCFs production technology pathways and references

LCF categories	Technology pathways	Fuel type	TRL	Reference
Renewable Electricity (RE)	electricity generation	RE	7~9	[1]
Green Hydrogen	Proton exchange membrane electrolysis (PEM)	Hydrogen	8~9	[37]
	Alkali electrolysis (AEC)	Hydrogen	8~9	
	Solid oxide electrolysis cell (SOEC)	Hydrogen	6~7	
Green Ammonia	Haber-Hosch (HB)	Ammonia	5~9	[17]
Power to Liquid (PtL)	Fischer-Tropsch process (FT PtL)	Kerosene	5~8	[18]
	Methanol Power-to-Liquid (MeOH PtL)	Kerosene	5~8	
Biomass to Liquid/Gas (BtX)	Anaerobic digestion	Biogas (Methane)	7~9	[9, 38]
	Thermal gasification	Methane, hydrogen	7~9	
	Esterification	Biodiesel (FAME)	8~9	
	Hydrotreating	Biodiesel (HVO)	8~9	
	Pyrolysis	Bio-oil	5~8	[31, 39]
	Hydrothermal liquefaction	Bio-oil	5~8	
	Catalytic hydropyrolysis	Bio-oil	5~8	
	Hydrolysis and Fermentation	Ethanol	3~5	[40]

LCF categories	Technology pathways	Fuel type	TRL	Reference
	Thermal gasification and FT process	Biodiesel	3~5	
	Syngas compression and methanol synthesis	Methanol	3~6	
Sun to Liquid (StL)	Solar reforming (SR)	Kerosene	4~6	[18]
	Solar reforming plus (SR+)	Kerosene	2~3	
	Pure solar thermochemical (ST)	Kerosene	3~4	
Blue Hydrogen	Steam methane reforming (SMR) with CCS	Hydrogen	8~9	[26]
	Autothermal reforming (ATR) with CCS	Hydrogen	8~9	
	Thermal decomposition (NGD) with CCS	Hydrogen	8~9	
	Auto-thermal chemical looping reforming (CLRa) with CCS	Hydrogen	6~7	[27]
Pink Hydrogen (nuclear H_2)	Conventional electrolysis (CE)	Hydrogen	5~7	[28]
	High temperature electrolysis (THE)	Hydrogen	5~8	
	3/4/5 step Cu-Cl cycle	Hydrogen	5~9	
Turquoise Hydrogen	Methane pyrolysis	Hydrogen	3~4	[30]
Blue Ammonia	Gas switching reforming (GSR)	Ammonia	6~8	[15]
Recycled Carbon Fuels (RCFs) from fossil wastes	Fermentation	Ethanol	6~7	[40]
	Catalytic synthesis	Methanol	4~6	
	Gasification and catalytic synthesis	Methane, Diesel	5~8	
	Pyrolysis and distillation	Diesel	7~9	

Table 6. Current TRL of production pathways to low carbon jet fuels [9, 18, 41]

Low carbon jet fuel categories	Technology pathways	TRL	Critical element
PtL (including green H_2 as feedstock)		5~8	CO_2 extraction from air
	Fischer-Tropsch (low temp)	6	Reverse water gas shift (RWGS)
	Fischer-Tropsch (high temp)	5	High-temperature electrolysis (SOEC)
	Methanol (low temp)	8	Final conversion
	Methanol (high temp)	5	SOEC, final conversion
BtL	Thermal gasification and FT	5-9	Gasifying feedstock other than wood
	HEFA (hydroprocessed Esters and Fatty Acids)	4~9	Feedstock (used cooking oil, palm, rape seed 9, algae 4-5)
	HTL (hydrothermal liquefaction)	4-6	Feedstock quantity

Low carbon jet fuel categories	Technology pathways	TRL	Critical element
	AtJ (sugar, starch based Alcohol to jet fuel)	5~9	Feedstock quantity
	SIP (sugar, synthesized iso paraffins)	5~9	Feedstock quantity
StL	SR/SR+/ST	5~6	Technology development

3.2 Cost indicators and process efficiency

Table 7 summarizes the capital expenditures (CAPEX) and production efficiencies in current literature in 2020s, 2035 and 2050 timeframe. It can be seen from the table that a complete and detailed assessment of low-carbon fuel technology and economy is lacking, including prospective data on development scenarios and paths. The research gap lies in the lack of a unified system to assess the production and development potential of low-carbon fuels. Due to the large gap between the current various studies on the assessment scenarios and unit settings.

*Table 7. Capital expenditures (CAPEX) / Production cost and process efficiency of LCF production technologies. Using 1 $ = 0.9 Euro, 1 $ = 1 CHF, 1 GBP = 1.15 Euro. The cost figures refer to year 2020. Fuel production efficiency is defined as LHV_{fuel}/total energy input)*100 if not specified. RE efficiency is defined as the energy efficiency of generator.*

Fuel Type				**CAPEX (CHF/kWe)**			**Efficiency (%)**			**Reference**
	LCF categories	Technology pathways	Fuel	2020	2035	2050	2020	2035	2050	
Electrification LCFs	Renewable electricity	Photovoltaics (PV)	RE[1]	780-3400	500-2400	450-2000	20-30	30-40	40-50	[10, 42]
		Wind power	RE[2]	2000-3000	1540 1940	1490-1870	45-50	n.a.	n.a.	
	Green Hydrogen	Proton exchange membrane electrolysis (PEM)	Hydrogen	1182	592	297	61	69	73	[10]
		Alkali electrolysis (AEC)	Hydrogen	988	676	462	67	69	71	
		Solid oxide electrolysis cell (SOEC)	Hydrogen	2710	1256	582	82	86	90	
	Green Ammonia	Haber-hosch (HB)	Ammonia	1600	1300	800	60-80	60-80	60-80	[17]
	Power to Liquid (PtL)	Fischer-Tropsch process (FT PtL)	Kerosene	3000	2000	1500	59	n.a.	n.a.	[19, 43, 44]
		Methanol Power-to-Liquid (MeOH PtL)	Kerosene	3000	2600	1000	40-69	n.a.	n.a.	

Fuel Type				**Production cost (CHF/ton)**			**Efficiency (%)**			**References**
	LCF categories	Technology pathways	Fuel	2020	2035	2050	2020	2035	2050	
Non-electrification LCFs	Biomass to Liquid/Gas (BtX)	Anaerobic digestion	Biogas (Methane)	1300	1200	1100[3]	75	77	83[4]	[9, 36, 38, 45, 46]
		Thermal gasification	Methane, hydrogen	1200-3500	n.a.	n.a.	69	n.a.	n.a.	
		Esterification	Biodiesel (FAME)	640	630	620	n.a.	n.a.	n.a.	
		Hydrotreating	Biodiesel (HVO)	760	640	600	85	n.a.	n.a.	
		Pyrolysis	Bio-oil	1000	700	300	62	64	65	
		Hydrothermal liquefaction	Bio-oil	3500			82	n.a.	n.a.	
		Catalytic hydropyrolysis	Bio-oil	1500	1100	930	57	58	60	
		Hydrolysis and Fermentation	Ethanol	2500	2200	2100	37	39	40	
		Thermal gasification and FT process	Biodiesel	4300	3900	3460	10.00	10.5	11.8	
		Syngas compression and methanol synthesis	Methanol	750-2700	n.a.	n.a.	61	63	65	
	Sun to Liquid (StL)	Solar reforming (SR)	Kerosene	1000-1500	n.a.	n.a.	4.1-5.6	n.a.	n.a.	[47-49]
		Solar reforming plus (SR+)	Kerosene	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
		Pure solar thermochemical (ST)	Kerosene	1700-1900	n.a.	n.a.	n.a.	n.a.	n.a.	
	Blue Hydrogen	SMR with CCS	Hydrogen	1000-2400	n.a.	n.a.	n.a.	n.a.	n.a.	[26]
		ATR with CCS	Hydrogen	1500	n.a.	n.a.	n.a.	n.a.	n.a.	
		NGD with CCS	Hydrogen	1300	n.a.	n.a.	n.a.	n.a.	n.a.	
		CLRa with CCS	Hydrogen	3000	n.a.	n.a.	n.a.	n.a.	n.a.	
	Pink Hydrogen (nuclear H_2)	Conventional electrolysis (CE)	Hydrogen	3000-5000	n.a.	n.a.	20-40[5]	n.a.	n.a.	[50, 51]
		High temperature electrolysis	Hydrogen	2500	n.a.	n.a.	40-70	n.a.	n.a.	
		3/4/5 step Cu-Cl cycle	Hydrogen	2200	n.a.	n.a.	70-90	n.a.	n.a.	
	Turquoise Hydrogen	Methane pyrolysis	Hydrogen	2600-3200	n.a.	n.a.	58	n.a.	n.a.	[30]
	Blue Ammonia	Gas switching reforming (GSR)	Ammonia	332	n.a.	192	65-71	n.a.	n.a.	[17]
	Recycled Carbon Fuels (RCFs) from fossil wastes	Fermentation	Ethanol	680-830	500-660	340-500	66	n.a.	n.a.	[31]
		Catalytic synthesis	Methanol							
		Gasification and catalytic synthesis	Methane, Diesel							
		Pyrolysis and distillation	Diesel							

[1] system capital costs with plant capacity from 1000kW to 6kW, efficiency is the module efficiency; [2] CAPEX data for Switzerland, efficiency does not change over time; [3] investment cost, CHF/kWe; [4] the percentage of producer gas of fuel input, [5] efficiency of NPP included

4. Discussion and outlook

4.1 Summary of the results

To summarize, 33 technology pathways are collected and explained for 11 kinds of LCFs in this report, together with technical and economic indicators from current literature and reports. The majority of the LCFs have reached a relatively mature level and development potential in terms of technology and scientific research. The current research lacks an economic and environmental assessment within a unified framework for a complete LCF portfolio. The data collected in this report provides a general reference, but the application potential in the future needs to be further analyzed as the development changes.

The current major studies indicate that the price of large-scale production of LCFs will drop significantly with the promotion of science and technology and through policies to create markets for these in the future. In the current development situation, their costs are still very high compared with conventional energy sources. As for Switzerland's emission reduction target, the selection of various LCFs in the energy structure needs to consider the carbon emissions and environmental impacts along the whole life cycle. The supply side, including raw materials, supply chain and environmental risks in the whole life cycle, needs to be especially considered. The role of low-carbon fuel in the carbon emission reduction of the transportation system is beyond doubt. After investigating the complete LCFs file, the subsequent analysis will reveal the economic costs, environmental benefits and their role in the energy system.

4.2 Project outlook and conclusion

For the SHELTERED project, the LCF matrix serves as the basis of WP1, as shown in the Figure 24. This report documents the first subtask “Technology specification”.

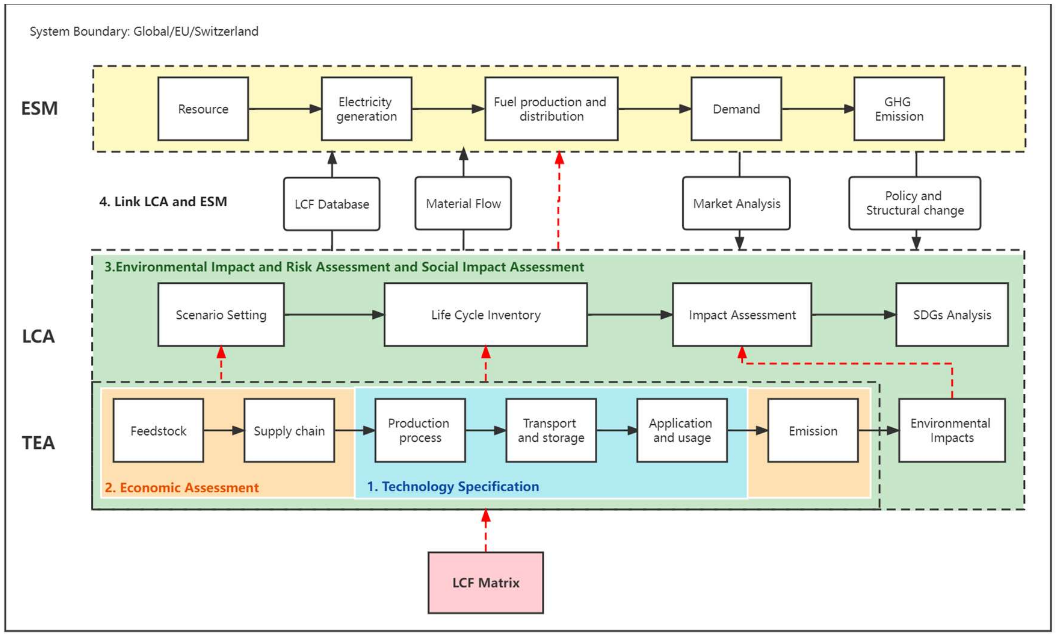


Figure 24. Planned SHELTERED project framework of Work Package 1

In the following subsections, several key issues are discussed, which will be addressed after completing the LCA and ESM analysis.

4.2.1 Supply chain and resource potentials

The cost of some LCFs and their carbon emissions in the whole life cycle depend to a large extent on the choice of raw materials and supply chains. Production regions and supply regions also determine the setting of analysis scenarios to a certain extent. The resource potential of low-carbon fuels depends on the input of raw materials and energy sources for production. For biofuels, biomass and land use potential determine the development prospects of biofuels. [40] Electrified fuel production relying on renewable electricity depends largely on the geographical location and supply system of renewable power plants. Low carbon fuels relying on CCS mainly need to consider the location and storage costs of carbon dioxide storage and the cost of raw material transportation. In order to qualitatively and quantitatively investigate resource potentials, the selection of raw material transportation, storage and supply chains should be considered for further economic and environmental impact analysis.

4.2.2 Sustainability and relations with sustainable development goals (SDGs)

Combining sustainable development goals is an international practice for evaluating sustainable indicators. SDGs are also closely related to the LCA part in WP1, and can provide more analysis perspectives from the perspective of social development. Currently, several studies of the sustainability assessment of LCFs investigated their contribution to SDGs. For example, renewable electricity[52] has a strong synergy effect with SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth). SDG 12 (responsible production and consumption) accounts for most of renewable electricity price variation.

In the existing literature, the assessment of the relationship between low-carbon fuels and SDGs is largely based on their LCA results in the future development process, including various environmental impact factors, potential carbon emissions, and social impact factors, such as promoting employment and scientific and technological development. To have a systemic relationship analysis between these indicators regarding LCFs and SDGs is also part of the sustainability assessment based on final LCA results.

4.2.3 Temporal scope and policy framework

The objectives, considering the time scale and policy framework, will be developed within a soft framework combining science and technology assessment and energy system analysis. The policy objectives guided by the assessment framework should be based on considering three aspects of development on the timeline, namely net zero carbon emissions, sustainable development goals and circular economy. Under the current, medium-term and long-term development paradigm, different policy scenarios will determine different development paths. Therefore, the assessment of LCFs will guide policy-making and development decisions.

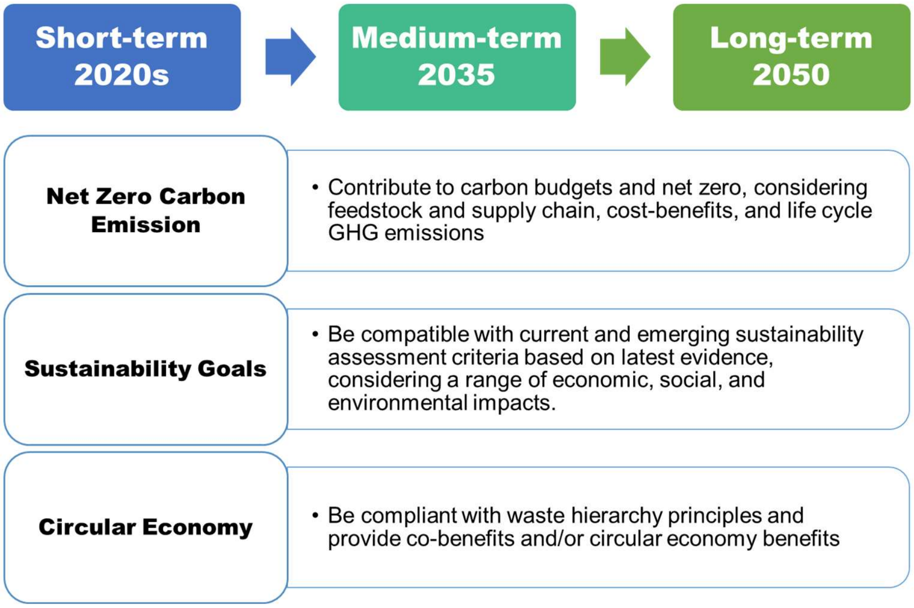


Figure 23. Policy goals of LCF strategy over three timescales: 2020s, up to 2035 and to 2050 [53, 54]

4.2.4 Conclusion

This report provides a complete overview of low-carbon fuels, including the production process, materials and energy input and output, as well as a summary of the current technology level and development stage. The existing literature lacks a systematic technical and economic assessment of low-carbon fuels and an analysis of the relationship between carbon emissions and sustainable development goals in the future development stage. The LCF matrix will be used as the basis and object of subsequent TEA and LCA model analysis to analyze their roles in the energy system and carbon emission reduction potential.

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