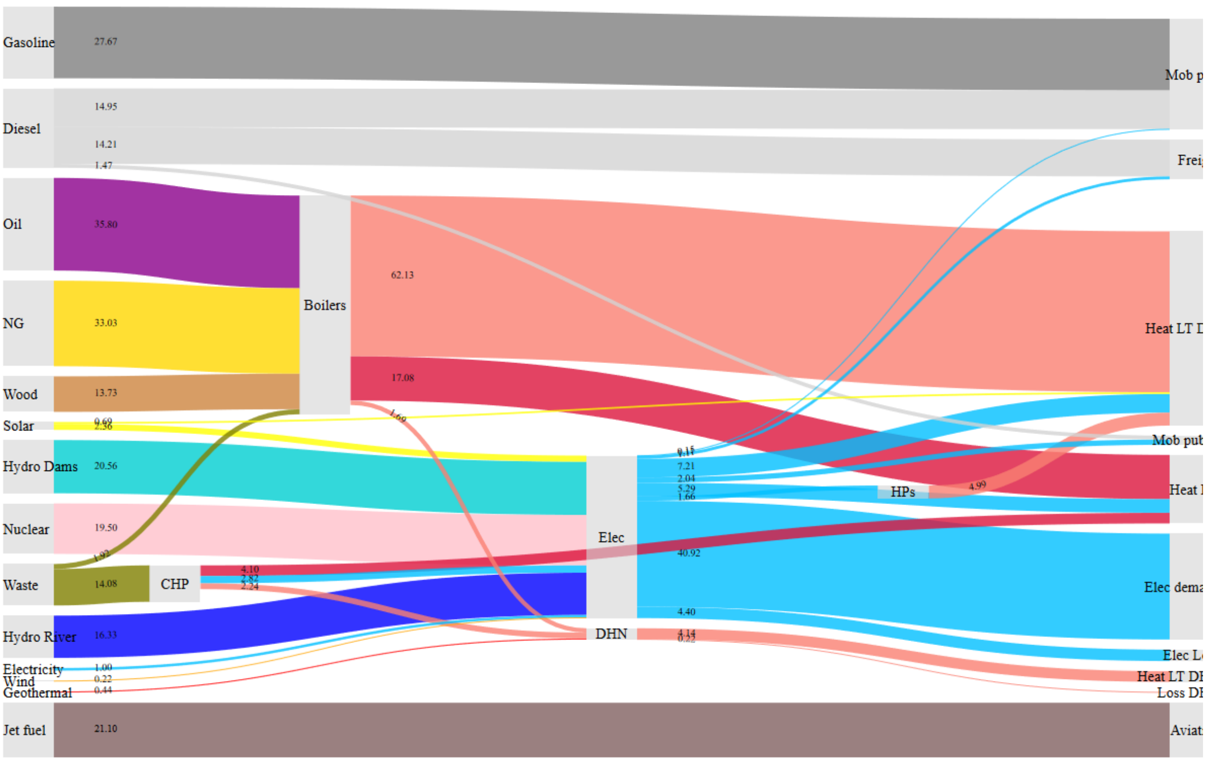
Final report

Carbon Flows in the Energy Transition

Extension of the project "Renewable Methane for Transport and Mobility"



HSR HOCHSCHULE FÜR TECHNIK RAPPERSWIL
FHO Fachhochschule Ostschweiz

EPFL

70 NRP Energy Turnaround
National Research Programme

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Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

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Summary

In the project “Carbon Flows in the Energy Transition”, a methodology is developed to monitor and assess the energy and carbon flows in the energy system of Switzerland. As the flows of carbon, either in the form of released CO_2 or stored in chemicals, are linked to the form and operation of the energy system, the design of the latter is crucial. Since the defossilization of the energy system is an important part to reach climate agreement goals, emphasis is given in renewables and biogenic carbon-containing resources, such as various forms of biomass and waste.

The potential of carbon and energy sources in Switzerland are evaluated in the first part of the project. In Switzerland, there is a yearly potential of 3.2 Mt wood (dry substance) and 3.1 Mt non-woody biomass (dry substance) for energetic use. Another carbon source is carbon dioxide from air or flue gases. While air has a small carbon dioxide content of 410 ppm, industrial sources provide flue gases with higher concentrations: cement plants (3.29 Mt_{CO2}/y), waste incineration plants (4.25 Mt_{CO2}/y) and sewage-treatment and biogas plants (1.1 Mt_{CO2}/y). Renewable energy sources are restricted as well. The above mentioned potential of wood corresponds to 14 TWh/y. The energy strategy from the Swiss Federal Office of Energy (SFOE) calculates with a potential of 38.6 TWh/y hydro power and 4.3 TWh/y wind power. A newly published study shows a potential for PV and thermal solar energy of totally 67 TWh per year, installed on roofs and building faces.

In the first part the demand in heat, mobility and electricity is evaluated as well. In the year 2017, the demand in space heating was 66.4 TWh/y, in hot water 12.7 TWh/y, in high temperature process heat 26.5 TWh/y and the demand in electricity was 40.9 TWh/y. Passengers travelled in total 132' 200 Mpkm, and freight was transported over 44'000 Mtkm. The demand in electricity was covered by hydro dams (20.72 TWh/y), running river hydro plants (15.95 TWh/y), nuclear power plants (19.50 TWh/y), combined heat and power plants, incl. waste incineration (2.80 TWh/y), PV (2.28 TWh/y) and wind power plants (0.22 TWh/y). Heat and mobility was covered by fossil fuels: Light fuel oil (35.54 TWh), Natural gas (33.03 TWh), diesel (31.82 TWh), gasoline (27.67 TWh) and jet fuels (21.10 TWh). Wood provided with 13.73 TWh also a large amount of energy. Heat pumps produced 4.64 TWh, and 0.69 TWh heat was provided by thermal solar.

In the second part of the project, energy and carbon conversion technologies (around 120 in total) were evaluated. These technologies include power plants, technologies for heating, cogeneration, mobility and transport, as well as biomass technologies, power-to-X-technologies and others.

The resulting data is incorporated into the existing infrastructure of Swiss EnergyScope (SES), an optimization algorithm for the design of energy systems and applied for the case of Switzerland. Using a formulation to account for the carbon content of the various streams within the energy system, both the energy and carbon flows can be tracked during the design of different scenarios related to future energy policies. A selected number of indicative scenarios are presented that can be used to investigate the necessary future actions towards nuclear phasing-out, defossilization and CO_2 taxation to name a few, with regard to the energy and carbon emissions profile of Switzerland.

Contents

List of abbreviations

BEV	Battery electric vehicle
CCGT	Combined cycle gas turbine
CCS	Carbon Capture and Storage
DACS	Direct Air Capture and Storage
EPFL	École Polytechnique Fédérale de Lausanne
FOEN	Federal Office for the Environment
HEV	Hybrid electric vehicle
HSR	Hochschule für Technik Rapperswil
HVACR	Heating, Ventilation, Air Conditioning and Refrigeration
IGCC	Integrated gasification combined cycle
GWP	Global warming potential
NG	Natural gas
NRP	National Research Programme
PHEV	Plug-in hybrid electric vehicle
RMTM	Renewable Methane in Transport and Mobility
SFOE	Swiss Federal Office of Energy
SNF	Swiss National Science Foundation
US	Ultra-supercritical

1 Introduction

In the context of the energy transition, there is much debate about energy flows and decarbonization. Little account is taken of the fact that carbon will continue to be indispensable for many applications after the energy transformation, such as plastics, chemical products and jet fuels. As source for these carbon based products, biomass as well as carbon dioxide can be used. Especially the latter may play a crucial role, as carbon dioxide is available in large amounts and so far this by-product is left unused.

In the project "Carbon Flows in the Energy Transition" an algorithm has been developed that models and allocates energy and carbon flows, in order to design efficient energy systems and identify the optimal energy and carbon paths, from carbon source (e.g. biomass or carbon dioxide) to carbon-based products (e.g. plastics or fuels). The objective function of the optimization can include economic and/or ecological aspects and the produced results help to derive decisions regarding the energy policy that can ultimately lead to efficient political measures. Although this algorithm is targeted towards the modeling of the carbon flows with a case study of Switzerland, it is of a generic structure and can be adapted for other energy systems of different scales as well.

In April 2018 the project “Carbon Flows in the Energy Transition” started as an extension of the project “Renewable Methane in Transport and Mobility (RMTM)”. It is carried out by a team both from Hochschule für Technik Rapperswil (HSR) and École Polytechnique Fédérale de Lausanne (EPFL). The project is part of the National Research Programme NRP70 and financed by the Swiss National Science Foundation (SNF), the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN) as well as by own funds.

1.1 Background and motivation

In order to reduce emissions from fossil fuels and to build an economy that is sustainable both ecologically and economically, various research projects have been carried out. These projects usually focus on one technology pathway and usually deal with the corresponding system disregarding the potential synergies of the resources with other technological pathways or energy systems. For example, biomass can be used either for biofuels, bioplastics or for heating by combustion. The ongoing project “Carbon Flows in the Energy Transition” is part of the National Research Programme NRP 70 “Energy Turnaround”. It takes a holistic approach and looks at all carbon flows associated to bio-based resources, flue gases, biofuels, biochemicals and plastics within Switzerland and across the borders (imports and exports).

For a successful energy turnaround, energy and product flows within Switzerland have to be investigated, with special regard to future demand. To form a fossil-free future of Switzerland, policy makers have to take measures. To determine which measures are most effective, this project traces the carbon flows in Switzerland and evaluates different pathways depending on different operating scenarios. The answers given by the project in the context of designing the optimal energy system with respect to a variety of operating modes will hint towards the necessary actions to be taken for a successful implementation in a fossil-free future.

1.2 Goals

Based on given forecast, the goal is the evaluation of scenarios to understand which are the most efficient pathways of carbon flows and therefore to take the most effective political measures. Questions like the following are answered in this project:

- What are the carbon resources in Switzerland and what will be their role as products or energy carriers? How much biomass is there in Switzerland (sustainable potential)?
- What are the available conversion technologies for biomass (cost, efficiencies, etc.)?
- What are the most cost and environmentally efficient ways of using limited biomass resources to meet the decarbonization targets?
- What are the technologies and the technoeconomic conditions of the integration of carbon sequestration and reuse in Switzerland?
- Should we use SNG directly for mobility or for electricity production and electric mobility?
- What will be the role of carbon harvesting and reuse in the energy transition and what will be the impact in terms of fossil CO_2 emissions?

1.3 Similar Projects

Most research projects focus on one subject. This of course makes sense because of their expertise in a field. Some more general publications to certain research fields are the following:

1.3.1 Power-to-X

In the field of Power-to-X, Carbon Capture and Utilisation (CCU) and Carbon Capture and Storage (CCS) multiple research projects have been launched and some publications are already available.

In August 2018, Dechema published the first Power-to-X roadmap for Europe (Ausfelder, et al., 2018). It includes political, economic and ecological aspects as well as system compatibility. In the context of CarbonNext – an EU project carried out by DECHEMA, the University of Sheffield and Trinomics – deliverables concerning the potential of CCU were published (DECHEMA, 2018).

Ramboll currently carries out another EU research project (Identification and analysis of promising technologies for carbon capture and use CCU (IASS, 2019)) in collaboration with IASS and University Kassel with the goal to identify the technologies in the field of the carbon dioxide use. SAPEA (Science Advice for Policy by European Academies) presents in a report a variety of novel carbon capture and utilisation technologies, see (SAPEA, 2018) and (Group, 2018).

In October 2018, Frontier Economics published on behalf of the World Energy Council – Germany the report: "International Aspects of a Power-to-X Roadmap". (Frontier Economics , 2018) The EU-project "Store&Go" focuses on the integration of PtG into the daily operation of European energy grids to investigate the maturity level of the technology. Three different demonstration sites offer testing grounds for PtG. Michael Sterner showed in his report (Sterner, 2017) the necessity of using Power-to-X technologies in future energy and product systems. METIS Studies, Study S8, made a forecast for the role and potential of Power-to-X in 2050. (Bossmann, et al., 2018)

1.3.2 Biomass

As a part of the Swiss energy strategy, eight Swiss Competence Centres for Energy Research (SCCERs) were created. One of them is SCCER BIOSWEET (https://www.sccer-biosweet.ch/), which is active in the field of bioenergy and focuses on research and implementation of biomass conversion processes. The main role of SCCER BIOSWEET is the assessment of the role of biomass in the Swiss energy transition. To achieve this, the project revolves around the design and evaluation of different biomass conversion pathways leading from the raw materials to useful services but also accounts for the design of the corresponding supply chains. This is expected to bridge the gap between the current conversion processes and set the transition from the process to the national level of design considering the economies of scale.

The H2020 project EUCalc (http://www.european-calculator.eu) aims to provide decision makers with a tool able to quantify the sectoral energy demand, greenhouse gas (GHG) trajectories and social implications of lifestyles and energy technology choices in Europe. It employs a model based approach to link emission reduction with human lifestyles, resource management, energy production, agriculture, process costs etc. While the project deals in general with integrated energy conversion systems, it also includes information on bio-based as well as CCUS technologies.

Lastly, the H2020 Waste2Watts project (https://waste2watts-project.net/) concerns the design of biogas to SOFC systems using an integrated scheme that leads from raw materials such as animal manure to biogas production, upgrade and use in solid oxide fuel cells for power production. The projects aims at displaying the effect of the biogas upgrading process as well as the scaling effect of the CO_2 removal and SOFC steps.

1.3.3 Models

In this project, the model is based on EnergyScope (SES – Swiss-EnergyScope), a model developed by the IPESE (Industrial Process and Energy Systems Engineering) group at the EPFL Valais and part of the SCCER JASM – Joint Activity Scenario & Modeling. EnergyScope is able to model energy pathways and optimizes them economically or ecologically with the focus of scenario analysis. Although the structure of the model is generic, it has been designed and applied with the focus on Switzerland.

Other energy models of Switzerland are developed by the ETHZ, the PSI and UNIBAS. The model by the PSI is called STEM (Swiss TIMES Energy Systems Model) (https://www.psi.ch/eem/stem), which focuses on transition scenario analyses and is also part of the SCCER JASM. The ETH Zurich works on a new model called Nexus. It is an integrated energy systems modelling platform.

There are several modelling tools developed for EU analysis.

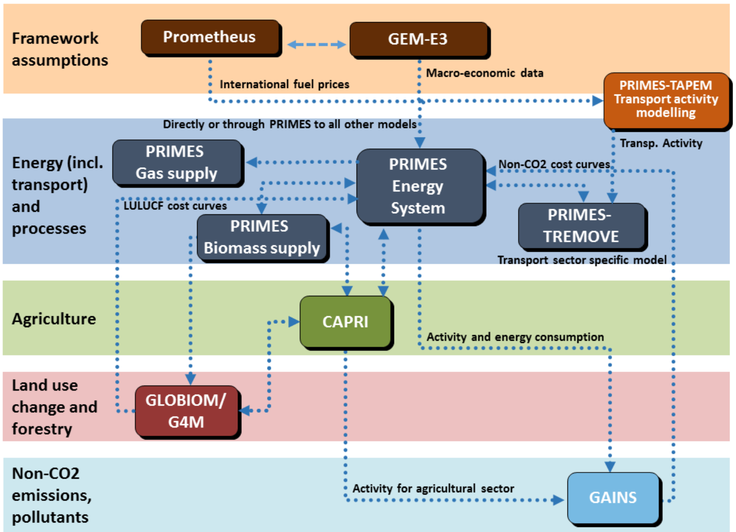

Figure 1. EU-Models. Source: https://ec.europa.eu/clima/policies/strategies/analysis/models

The models cover all GHG emissions and removals:

- Emissions: CO_2 emissions from energy and processes (PRIMES), CH_4, N_2O, fluorinated greenhouse gases (GAINS), CO_2 emissions from LULUCF (GLOBIOM-G4M), air pollution SO_2, NO_x, PM2.5-PM10, ground level ozone, VOC, NH_3 (GAINS).

- Emission reduction and removals: structural changes and technologies in the energy system and industrial processes (PRIMES), technological non-CO_2 emission reduction measures (GAINS), changes in land use (GLOBIOM-G4M-CAPRI).
- Time horizon: 1990 to 2050 (5-year time steps).
- Geography: individually all EU Member States, EU candidate countries and, where relevant Norway, Switzerland and Bosnia and Herzegovina.
- Impacts: on energy, transport, industry, agriculture, forestry, land use, atmospheric dispersion, health, ecosystems (acidification, eutrophication), macro-economy with multiple sectors, employment and social welfare.

2 Carbon Sources

For significant results of the project, a reliable data basis is crucial. In the first part of the project, a data collection of all carbon sources in Switzerland is generated. These sources are divided into four sections:

- Woody biomass: Forest wood, wood from landscape maintenance, wood residues, waste wood.
- Non-woody biomass: Crop farming, animal farming, organic fraction of household waste, green waste from households and landscape, commercial and industrial organic waste, sewage sludge from central treatment plant, industrial food and meat production.
- Carbon dioxide: Atmosphere, cement-manufacturing plants, waste-incineration plants, biogas / sewage plants, fuel combustion for transport, fuel combustion for heating, industrial processes.
- Imports: Plant-based food, fossil fuels, chemicals, paper / wood, consumer goods, plastics and rubbers, animals, animal-based food, fabrics, stone and base materials.

The potential of each of these carbon sources is elaborated by the following approach:

1. Definition of the theoretical potential (total available yearly amount, in 10^6 kg per year), the uncertainty of this figure (in %), the carbon content (in %, kg carbon per kg mass) and the energy content (in MJ/kg).
2. Definition and subtraction of the already used potential (in form of goods like furniture e.g.) in 10^6 kg per year.
3. Definition and subtraction of the economical-technical restriction (e.g. woods in remote areas), in 10^6 kg per year.
4. Supply costs in CHF/GJ or CHF/t respectively, with the corresponding uncertainty.

Nineteen domestic carbon sources are identified (excluding imports which are assumed to be unlimited, compared to the Swiss demand). Four categories of carbon sources are defined (woody biomass, non-woody biomass, CO_2 sources and net imports), all of them consisting of several carbon sources.

The potential of each of the different sources can be subdivided into four terms. The ”theoretical potential” of each carbon source is the total amount that is available in Switzerland. Here the specific properties of the feedstock are provided (i.e. carbon mass fraction and specific energy per mass). The ”already used potential” refers to the amount already sed for energy purposes. Finally, the ”economical-technical restrictions” express the quantity of economically and / or technically not harvestable sources (e.g. harvesting wood from trees in remote mountain areas may not be economically feasible).

$$total\ potential = theoretical\ potential - already\ used\ potential - economical/technical\ restrictions$$

At the end, the available total potential is the theoretical potential from which the already used potential as well as the economical-technical restrictions have been subtracted. The total available carbon contained is then calculated based on the carbon content of of the source (potential multiplied by the carbon mass fraction). The energetic potential is also calculated by multiplying the source potential by the specific energy content. Additionally, the costs of the different sources are taken into account.

The largest potential after subtracting the already used potential as well as the economical-technical restrictions are attributed to the carbon dioxide sources. The atmosphere is regarded as an infinite carbon dioxide source, however with a low carbon dioxide content (around 410 ppm). Waste incineration plants and cement manufacturing plants represent good carbon sources as they are currently unused and have a higher carbon content than the atmosphere (around 10 to 35 % v/v (Meier, et al., 2017)). The figures are based on research done by Thees et al. (2017) and on the previous project “Renewable methane for transport and mobility” (Meier et al, 2017).

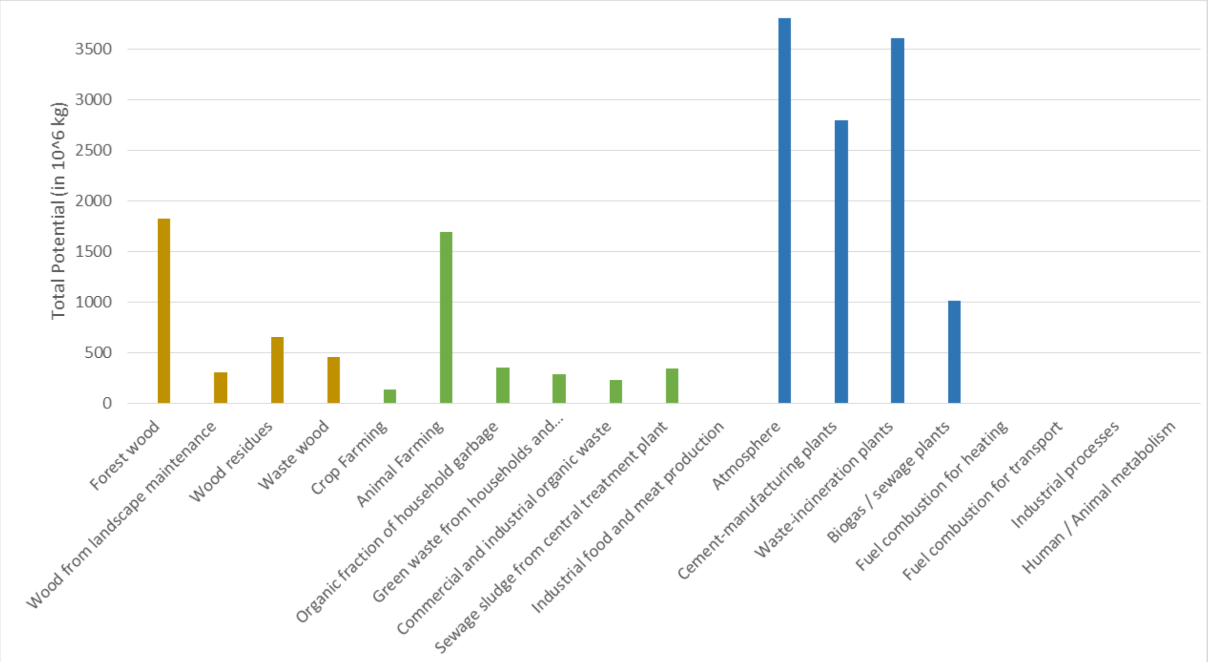

Figure 2. Total potential of domestic carbon sources in 10^6 kg (dry matter) per year: Woody biomass (brown), non-woody biomass (green), carbon dioxide (blue), after subtracting the already used potential as well as economical-technical restrictions. Sources, that are difficult to use or too expensive have a total potential of zero kilograms (e.g. carbon dioxide emissions from cars). Sources: (Thees, et al., 2017) and (Meier, et al., 2017).

2.1 Woody biomass

For the figures of the potential of woody biomass, studies by (Thees, et al., 2017) as well as by ZHAW ((BAFU, BFE, BLW, 2008) and (BAFU, BFE, BLW, 2009)) are consulted. As both references show similar results, the figures from (Thees, et al., 2017) are taken for the result table.

The category "woody biomass" consists of four different sectors: Forest wood, wood from landscape maintenance, wood residues and waste wood. All figures describing the quantity (i.e. the mass) of the potentials are a result of a study carried out by the Swiss Competence Centre for Bioenergy Research (SCCER BIOSWEET), see (Thees, et al., 2017). The uncertainty of the mass is assumed to be 5 %. This number is based on an information by the ZHAW who carried out a study of the biomass flows within Switzerland and received similar figures to those by SCCER BIOSWEET . As the quantity of the mass refers to dry mass, the carbon content is approximately 50% (see (Meier, et al., 2017)). The energy content of the different woody biomass sources is provided by the (Thees, et al., 2017) as well.

Woody biomass is a special case as many trees grow in remote, inaccessible places. This is represented in the section "economical-technical restrictions". The costs are provided by (Thees, et al., 2017). For the costs an uncertainty of 10 % is assumed as no information is provided.

In the strategy paper on wood resources the Swiss Federal Offices of Environment, Energy and Economy present their plans for the use of wood energy (BAFU, BFE, SECO, 2017):

Table 1. Potentials of woody biomass.

Carbon source	*Theoretical potential, ds (kt/y)*	*Already used potential, ds (kt/y)*	*Economical-technical restrictions, ds (kt/y)*	*Total potential, ds (kt/y)*	*Total potential (TWh/y)*	*Supply Costs (CHF/GJ)*
Forest wood	7'348	4'612	913	1823	7.41	14.0
Wood from landscape maintenance	606	0	301	305	1.31	6.0
Wood residues	798	145	0	653	3.27	2.0
Waste wood	1'456	833	165	458	2.09	1.0
Total	10'208	5'590	1'379	3'239	14.08	

In 2017, wood provided around 9.6 TWh/y of energy. Therefrom, 500 GWh/y were used for electricity production. (BAFU, 2018)

2.2 Non-woody biomass

Non-woody biomass includes all biomass produced in Switzerland including the whole outcome of agriculture, grasslands and biogenic waste from industry and households including sewage plants.

The whole table is divided, like before with the woody biomass, into four parts . In the first part, the theoretical potential of non-woody biomass is described. This is the total amount that is annually available in Switzerland including food and feed production. For the non-woody biomass, the economical-technical restriction is the one of the more expensive and resource-intensive products like the ones from animal farming. Additionally, the costs are listed. The information is based on the study by SCCER BIOSWEET (Thees, et al., 2017) as well. Here an uncertainty of costs of 10 % is assumed as no information is provided.

Table 2. Potentials of non-woody biomass.

Carbon source	*Theoretical potential, ds (kt/y)*	*Already used potential, ds (kt/y)*	*Economical-technical restrictions, ds (kt/y)*	*Total potential, ds (kt/y)*	*Total potential (TWh)*	*Supply Costs (CHF/GJ)*
Crop Farming	9'340	8'553	652	135	0.56	1.0
Animal Farming	3'811	1'161	956	1'694	7.51	7.0
Organic fraction of household garbage	352	0	0	352	1.67	0.0
Green waste from households and landscape	293	0	0	293	1.20	-1.0
Commercial and industrial organic waste	1'027	0	789	238	0.88	4.5
Sewage sludge from central treatment plant	347	0	0	347	1.35	4.5
Industrial food and meat production	2'430	2'430	0	0	0	0.0
Total	17'600	12'144	2'397	3'059	13.17	

As the study carried out by SCCER BIOSWEET only covers the waste from crop production, the figures from a study by the ZHAW about the biogenic mass flows within Switzerland (2006, updated in 2009) are used to supplement the data. These can be found in (BAFU, BFE, BLW, 2008) and (BAFU, BFE, BLW, 2009).

2.2.1 Crop farming

The theoretical potential of crop farming used in the project is summarized in the following table.

Table 3. Distribution of the output of crop farming in kilotons dry substance (ds) per year.

	Mass (ds) (kt/y)	*%*	*Reference*
Crop by-products	787	8.4	(Thees, et al., 2017)
Animal Feed	7'467	80.0	(BAFU, BFE, BLW, 2009)
Food	1'055	11.3	(BAFU, BFE, BLW, 2009)
Seeds and non-food products	31	0.3	(BAFU, BFE, BLW, 2009)
total	9'340	100	

The crop by-products include, next to the harvest residues, the amount of the currently used biomass for energy carriers and fermentation as well. The carbon content is typically around 45 % for all crop-farming products as the mass is given as dry substance. An uncertainty of 5 % in the data is chosen based on information by the authors.

In 2006, crop farming had according to (BAFU, BFE, BLW, 2008) an energy input of 12.7 TWh/y, and an energy output of 38.0 TWh/y (proportion ~ 1 to 3). The mass input was 2’852’578 t/y in total (ds), the mass output 7’934’861 t/y (ds) (proportion 1 to 2.8). The crop farming has almost three times more output than input in regards to biogenic energy and mass, the rest is gained through photosynthesis.

2.2.2 Animal farming

Animal farming had in 2006 according to (BAFU, BFE, BLW, 2008) an energy input of 38 TWh/y, and an energy output of 16 TWh/y (proportion ~ 2.4 to 1). The mass input was 8’157’321 t/y in total (ds), the mass output 3’398’625 t/y (ds) (proportion 2.4 to 1). Animal farming therefore has 2.4-times more input than output in regards to energy and mass. Currently the output of animal farming is mainly used as fertilizer for the plant industry.

Table 4. Distribution of the output of animal farming (BAFU, BFE, BLW, 2009).

	Mass (ds) (kt/y)	*%*
Food	434	11
Slaughtered animals	222	6
Animal Manure	3'060	80
Wool	0.4	0
Milk for feeding	72	2
Export	23	1
Total	3'811	100

By far the largest output of animal farming is the manure of the animals. According to Thees et al. (2017), this figure was distributed among the different animals themselves again (76% by cows, 11% by horses, rest by sheep, pigs, goats and poultry). The corresponding figures are listed in Table 4. The cost of animal manure has been set to zero as it is considered a waste.

2.2.3 Waste

Household garbage is split into a biogenic fraction, paper and cardboard, and other organic products.

Table 5. Parameters of organic fraction of household garbage (Thees, et al., 2017).

	Dry substance ds (%)	*Carbon Content (in % of ds)*	*LHV (MJ / kg ds)*	*Theoretical potential (kt/y ds)*
Biogenic fraction	36	39.0	14.7	177
Paper	70	49.6	18.5	158
Cardboard	60	51.2	20.0	
Other Org. Products	77	52.2	21.0	17
Total				**352**

The figures for green waste from households and landscape maintenance, as well as the figures for sewage sludge from central treatment plants, are described at the beginning of this chapter and do not require a more detailed analysis. Commercial and industrial organic waste has different origins; the main ones are mentioned in the following table:

Table 6. Parameters of commercial and industrial organic waste (Thees, et al., 2017).

Carbon source	*Theoretical potential (kt/y)*	*Already used potential (kt/y)*	*Economical-technical restrictions (kt/y)*	*Total potential (kt/y)*
Food processing	579	0	407	172
Catering	36	0	3	33
Retail trade	39	0	13	26
Printing Industry	346	0	346	0
Others	27	0	19	8
Commercial and industrial organic waste	1'027	0	789	238

All figures for the organic fraction of the household garbage, the green waste from households and landscape, the commercial and industrial organic waste and the sewage sludge are from the SCCER

BIOSWEET study (Thees, et al., 2017), including the costs. Uncertainties of 5% are assumed regarding the quantity and 10% regarding the costs. All carbon mass fractions are approximately 45% (given dry substances). These figures are from the project RMTM (Meier, et al., 2017).

2.2.4 Industrial food and meat production

In the section "Industrial food and meat production" the actually consumed output of the food and meat industry is listed (from which the waste was described in the previous four sections). The figures in this sections are based on the ZHAW study (BAFU, BFE, BLW, 2009). Industrial food and meat production is divided in four sections: Plant-based food: (2'430 kt/y), Animal-based food (2'287 kt/y), animal feed (16 kt/y), skin and fur (14 kt/y), which gives a total theoretical potential of 2'430 kt/y. As these quantities are directly consumed by humans or animals, the theoretical potential is the same as the already-used potential. Therefore these sources cannot be used for carbon harvesting and the remaining mass potential is zero.

2.3 Carbon dioxide

A previous study at the IET (Meier, et al., 2017) about Swiss carbon sources shows that it is feasible to capture annually a carbon mass flow of 1'500 kt/y only by using the flue gas from the larger incineration plants and cement manufacturing plants.

The total emitted amount of CO_2 by vehicles and for heating purposes is the largest one. However, divided by the number of plants or emitters, the amount per emitter is by far higher in cement-manufacturing or waste incineration plants. It is therefore much more efficient to harvest carbon dioxide there. In the large plants, a capture rate of 80% is reasonable (see (Design, Functionality and Emissions of the Amine Plant, 2001) and (Rao, et al., 2002)). Therefore, the economical-technical restrictions correspond to 20% of the theoretical potential.

Table 7. Carbon dioxide sources in Switzerland and their potentials (Meier et al., 2017).

Carbon source	*Theoretical potential (ds) (kt/y)*	*Already used potential (kt/y)*	*Economical-technical restrictions (kt/y)*	*Total potential (kt/y)*	*Total potential (TWh)*	*Capture Costs (CHF/t CO_2)*
Atmosphere	Unlimited	0.9	0	Unlimited	0	92-230
Cement-manufacturing plants	3'290	0	494	2'797	0	25-40
Waste-incineration plants	4'250	0	638	3'613	0	50
Biogas / sewage plants	1'191	0	179	1'012	0	0-100
Fuel combustion for heating	17'740	0	17'740	0	0	-
Fuel combustion for transport	21'517	0	21'517	0	0	-
Industrial processes	5'620	0	5'620	0	0	-

Human / Animal metabolism	13'650	0	13'650	0	0	-

The first part of the table specifies the sources. The figures as well as the uncertainties are a result from the pre-going study "RMTM" (Meier, et al., 2017). There they also define the carbon dioxide fraction, which is around 410 ppm in the atmosphere and above 10% in flue gases. As carbon dioxide is a result of a completed reaction, the energy level of it is zero. For the reason that the atmosphere is not nationally restricted, it is assumed an infinite source.

At present, there is hardly any regaining of the carbon dioxide. Climeworks built a plant in Hinwil in 2017, which captures 2'460 kg of CO_2 per day (Climeworks, 2018). As this is a new, still developing innovation, the costs are today 600 Swiss francs per ton CO_2. However, they claim that carbon dioxide might be harvested from the atmosphere for 100 Swiss francs per ton once the technology is further developed and the costs could be lowered. Currently, 900 tons CO_2 per year are captured at their plant. This is the figure shown in the table in the section "already used potential".

Technically and economically it is too expensive to harvest the emissions of a large number of small emitters like cars and houses. Therefore, the figures of these sources are the same in the part "economical-technical restrictions" as in the theoretical potential. And the total potential of them are zero.

In the European Union's Horizon 2020 research and innovation programme "Store & Go" carbon capture and Power-to-Gas processes are analysed. In their assessment of literature data about the CO_2 supply, they report the following average capture costs for CO_2:

Table 8. Average CO_2 capture costs related to industrial sectors (Böhm, et al., 2018).

	CO_2 Source	***Capture costs ($€/t_{CO2}$)***	***Year***	***Reference***
Energy industry; power & heat from fossil fuels (CO_2 from combustion processes in power plants)	Coal	34-42	2017	(Bains, et al., 2017)
		19-47	2015	(Reiter, et al., 2015)
		20-63	2015	
		48	2011	(Socolow, et al., 2011)
	Natural Gas	63-83	2017	(Bains, et al., 2017)
		54-101	2015	(Reiter, et al., 2015)
		35-75	2015	
	Biomass	54-101	2015	(Reiter, et al., 2015)
Chemical industry	Refinery	29-83	2017	(Bains, et al., 2017)
		44-94	2015	(Reiter, et al., 2015)
		48	2012	
		97	2014	
	Ammonia Production	12	2017	(Bains, et al., 2017)
		23-54	2015	(Reiter, et al., 2015)
		22	2014	
	Other chemicals	12-52	2017	(Bains, et al., 2017)
		21	2014	
Iron and steel production		19-33	2017	(Bains, et al., 2017)
		16-41	2015	(Reiter, et al., 2015)
		81-83	2014	
Cement, clinker & lime production		22-35	2017	(Bains, et al., 2017)
		33-69	2015	(Reiter, et al., 2015)
		17-37	2012	

	CO2 Source	Capture costs (€/t_{CO2})	Year	Reference
		82	2014	
Pulp, paper & board production		18-27	2003	
		57-87	2017	
Biogenic CO_2 Source	Biogas upgrading	0-90	2012	
		5-9	2015	(Reiter, et al., 2015)
	Bioethanol fermentation	12	2017	(Bains, et al., 2017)
		0-18	2011	
		25	2014	
		5-9	2015	(Reiter, et al., 2015)
	Bioethanol fermentation (incl. cogeneration)	83-111	2011	
		42	2003	
Direct air capture		150-320	2012	(Trost, et al., 2012)
		22	2012	(Trost, et al., 2012) (Lackner, 2009)
		150	2010	
		331-423	2011	(Socolow, et al., 2011)
		268-309	2013	(Mazzotti, et al., 2013)
		341-475	2014	
		81-201	2018	(Keith, et al., 2018)

Biogas plants supplying natural gas into the natural gas grid are a very good CO_2 source. The effort of carbon dioxide capture and sequestration is normally already done for the retrieval of biomethane which can then be fed into the natural gas grid and therefore the costs are assigned to the methane production. In this aspect, the sequestration of CO_2 is neutral in costs (Böhm, et al., 2018) (based on (Trost, et al., 2012) and (Reiter, et al., 2015)).

2.4 Imports

Now, most carbon-based products and fuels are imported to Switzerland, as are for example plastics and gasoline. Thus, it is evident that imports are an important category of carbon sources. Compared to the global availability of carbon-based products, the Swiss import rate is small enough for not taking any restrictions of imports into account. For example, compared to the worldwide availability of gasoline, the Swiss demand is small enough so that there is no restriction due to a potential lack of availability.

Therefore, all imports are considered unlimited. However, for the products and fuels that are produced abroad, the carbon dioxide emitted during production is considered along with the imports. (Boustead, 2005) define in their study the gross air emissions associated with the production of 1 kg of polyols. A carbon dioxide content of 2.9 kg per kg of polyol was defined. This value is used for the calculations of the abroad emissions for all plastics.

3 Carbon Demand

Energy and carbon flows are closely connected. For this reason, first the energy demand is investigated. The need of organic chemicals and plastics is determined by the current imports as there is hardly any production at the moment in Switzerland. The demand is defined in GWh/y for the energy flows and in 10^6 kg/y for product flows.

Apart from chemicals and plastics, the carbon demand varies immensely depending on the final product used. It is possible, for example, to cover the entire mobility and heat demand with or without hardly any carbon-based technologies involved (except for planes). For this reason, the end demand in mobility (car traffic, public transportation as well as freight transport) and the heat demand (high and low temperature heat) are defined, without specifying which energy-carrier will be used.

For the further steps with the model the end demand will change depending on the scenario used. For example, a scenario could be the ban on diesel cars or that all citizens travel only by public transportation. However, in this chapter, the focus is on the current situation.

3.1 Mobility and Transport

In 2015, each Swiss citizen (over 6 years old) travelled a distance of 24'849 km/y on average. From this, 13'754 km/y (55%) were domestic travels, and 11'095 km/y (45%) international journeys. The most important means of transport is the car with 10'371 km per person and year, second is the plane with 8'986 km/y (BFS, 2019).

3.1.1 Passenger and Freight Mobility

Private cars covered a distance of total 94'000 Mpkm/y, trains covered 21'000 Mpkm/y and public busses around 4'000 Mpkm/y (BFS, 2019). This makes a total of 119 Mpkm/y. On the Swiss roads a total of 17'200 Mtkm/y was performed for freight transport in 2017, while trains covered around 10'100 Mtkm/y (BFS, 2019).

3.1.2 Planes

In 2017 (according to (BFS, 2018)):

- 24.9 million journeys of Swiss citizens with at least one non-resident overnight stay took place.
- 33% of these journeys were within Switzerland, 40% to a neighbouring country, 20% within Europe and 7% outside of Europe.
- 43% of the journeys abroad from Swiss citizens were done by aviation.

If it is assumed that all journeys to a destination outside of Europe are done by plane, there were 1.743 million long-distance journeys and 5.431 million short distance flights. In 2017, 1'723'717 tonnes of fuel were filled up in Switzerland. Within the Swiss airspace a total of 582'674 tonnes per year of fuel were consumed (BFS, 2018).

According to (BFS, 2018) there were 100'000 million passenger-km/y performed in incoming and outgoing scheduled and charter traffic, with Zurich being the largest airport (70'000 million passenger-km per year). These figures represent the actually performed passenger-km. In 2015 a total of 125'000 million passenger-km were offered for incoming and outgoing scheduled and charter traffic (the seat load factor is 80% on average (FSO, 2018)).

For the year 2017, FSO also defines the fuel consumption which is 1'724'000 t/y filled up in Switzerland, and 583'000 t/y consumed in the Swiss airspace. Given the quantity actually filled up in Switzerland, the carbon dioxide emissions are calculated to be 5'400'000 t/y (FSO, 2018).

Kerosene has a density of 0.78-0.81 g/cm^3, a specific energy of 42.8 MJ/kg and an energy density of 37.4 MJ/l.

3.2 Heat

According to recent reports (BFE - Prognos, 2018) the Swiss heat demand was 105.6 TWh/y in total in 2017. Around 25% of the heat consumed is high temperature heat for industrial processes while 75% of the heat demand is low temperature heat for space heating and hot water. (BFE - Prognos, 2018) defines three different kind of heat demand:

- Space heating includes the energy consumption of fixed heating installations as well as the consumption of mobile heating systems (e.g. electric heating). (The energy demand of heating installations for the control system and pumps belong to the category "ventilation, air conditioning and refrigeration" and are covered in the electricity demand.)
- Process heat includes the heat demand in industrial and commercial operating processes as well as the electricity demand in the kitchen (cooking stove and steamer).

Table 1. Swiss Heat Demand in 2017 (GWh/y) (BFE - Prognos, 2018)

	Households	*Services*	*Industry*	*Transportation*	*Total*
Low Temperature Heat – Space Heating	44'140	18'000	4'310	0	66'450
Low Temperature Heat - Hot Water	8'920	3'080	720	0	12'720
High Temperature Heat - Process Heat	1'530	580	24360	0	26'470
Total domestic energy demand	54'590	21'660	29'390	0	105'640

3.3 Chemicals and Plastics

Together with the demand in form of heat, mobility, electricity and lighting, the demand in organic chemicals as well as plastics is considered with focus on the most common ones. In the year 2017, the import of organic chemicals was dominated by the following products (see Appendix - Section 11.5):

1. **Acetone, annual demand: 54.0 kt, Import price: 0.8 CHF/kg**
2. *Esters of acrylic acid, 48.8 kt, Import price: 1.7 CHF/kg*
3. **Acetic Acid, annual demand: 47.4 kt, Import price: 0.5 CHF/kg**
4. *Aromatic monoamines, 36.9 kt, Import price: 3.5 CHF/kg*
5. **Methanol, annual demand: 36.6 kt, Import price: 0.4 CHF/kg**
6. **Phenol, annual demand: 36.5 kt, Import price: 1.1 CHF/kg**

7. **Ethanol, annual demand: 36.3 kt, Import price: 1.4 CHF/kg**

It is considered that the current demand is equal to the current import. The plastic imports are dominated by the following products (see Appendix - Section 11.5):

1. **Polyethylene, annual demand: 208.2 kt, Import price: 1.5 CHF/kg**
2. **Polyethylene terephthalate, annual demand: 95.8 kt, Import price: 1.1 CHF/kg**
3. **Polyvinyl chloride, annual demand: 84.3 kt, Import price: 1.1 CHF/kg**
4. *Plates, sheets, film, foil and strip, of non-cellular plastics*, 80.1 kt*, Import price: 3.2 CHF/kg*
5. **Polypropylene, annual demand: 75.1 kt, Import price: 1.5 CHF/kg**
6. *Urea resins and thiourea resins, in primary forms, 65.9 kt, Import price: 0.4 CHF/kg*
7. *Articles of plastics and articles of other materials of heading 3901 to 3914, n.e.s, 57.0 kt, Import price: 14.3 CHF/kg*
8. **Polystyrene, annual demand: 56.2 kt, Import price: 1.5 CHF/kg**

Currently, the Swiss plastic demand is covered by imports. In 2017, Switzerland imported totally 1'728 ktons of plastics and articles thereof (see (Swiss-Impex, 2019) or Appendix - Section 11.5). However, in the same year, the export was in total 915 ktons of plastics per year, which results in a net import of 8'114 ktons of plastics per year.

With an increasing number of recycling processes, the total import demand and therefore the carbon dioxide emissions associated with the production abroad can be reduced (around 2.9 kg CO_2 per kg plastics (Boustead, 2005) at the moment). The recycling processes are not included in the model currently, but implicitly accounted in the net import figures. For example, a reduction in the plastics imports by 50% would be equal to a recycling rate of 50% if the demand remains the same.

In Switzerland the recycling rate was around 25% in the year 2018, and the rest (75%) is incinerated and used for electricity and heat production (PlasticsEurope, 2018). Switzerland is one of the European Union (EU) top trade partners for plastics (PlasticsEurope, 2018).

Polyethylene-based materials (PE-LD, PE-LLD, PE-HD, PE-MD, PET) as well as polypropylene are mainly used for packaging purposes. However, the use of polypropylene (PP) is more evenly distributed as it is also used in other sectors (building & construction, automotive, electrical & electronic devices, agriculture, household/leisure/sports). Polyvinylchloride (PVC) is used in buildings and construction.

3.4 Negative Emissions

Many predictions for the future development of carbon flows include negative emissions, i.e. carbon dioxide that is captured from the atmosphere or flue gases and stored underground. A consortium of Icelandic utility Reykjavik Energy and Swiss company Climeworks has successfully tested Direct Air Capture and Storage (DACS) technology in Iceland. According to their press release in October 2018 (Climeworks, 2018) this consortium named ”CarbFix” will start now the project-planning phase for expanding their DACS capacity. It will be the first plant to remove carbon dioxide from the atmosphere and store it in the ground. In their latest report, the IPCC made clear that for avoiding a major raise in temperature, a crucial reduction in carbon dioxide emissions whilst at the same time remove CO_2 from the atmosphere (Rogelj, et al., 2018). Climeworks has declared their goal of capturing one per cent of global emissions by 2025 (Climeworks, 2018).

For the CarbFix2 project In Hellisheidi in Iceland Reykjavik Energy, ON Power and Climeworks are now planning an expansion of their DACS capacity. (Gunnarsson et al., 2018) defines the costs of carbon capture at the CarbFix2 site to be $25/ton of the gas mixture.

Table 10. Cost of mixed gas capture (54.4 vol% CO_2 and 22.7 vol% H_2S) and storage at the CarbFix2 site (Gunnarsson et al., 2018) (CHF/t).

	Case 1	Case 2	Case 3
Capture	21.3	21.3	42.1
Transport	1.3	1.3	1.3
Injection	1.3	4.1	4.1
Monitoring	0.9	0.9	0.9
Total CCS Cost	24.8	27.6	48.4

Assumption: $ 1 = CHF 1. Case 1: On site up-scaled cost at Hellisheidi power plant. Case 2: On site up-scaled cost at Hellisheidi power plant including drilling a well for injection. Case 3: On site up-scaled cost at Hellisheidi power plant including drilling a well and using average OECD electricity price for industry in 2014 (US$ 123.9/MWh).

The relatively low cost derive from optimal conditions in Iceland. In Hellisheidi the exhaust gas is concentrated and heat is available for free.

Table 11. Carbon capture costs derived from literature study results (CHF/t), from (Rubin et al., 2015), (WorleyParsons Services Pty Ltd., 2011) and (Rackley, 2009).

Process	Industrial carbon source	Direct air capture
Capture	50	300
Transport	1.3	1.3
Injection	4.1	4.1
Monitoring	0.9	0.9
Total CCS Cost	56.3	306.3

4 Conversion Technologies

For converting the carbon sources into usable products, different pathways are taken into account. The definition of the conversion technologies takes the following factors into account:

- Reference plant size (GW)
- Investment costs (CHF / kW)
- Maintenance costs (CHF / kW_{th} / year)
- GWP of construction
- Lifetime (in years)
- Input and Output (in kW or kg).

The technologies themselves are divided in six sectors:

1. Energy conversion technologies (Moret, 2017)
2. Hydrogen: Although not explicitly associated to carbon, hydrogen is a necessary component for many carbon conversion technologies.
3. Renewable Fuels: This section is comprised of technologies that have methane, diesel, gasoline, coal or kerosene as end products, produced from renewable input materials.
4. Organic Chemicals: In this section, the end products are acetic acid, methanol, ethanol, phenol and acetone. These are the most common organic chemicals.
5. Intermediates: To produce bioplastics, intermediate products like ethylene, propylene, styrene and benzene are required. These are covered in this section.
6. Plastics: In the last section, the intermediates are converted into plastics.

4.1 Biomass to X

In this section, a short description of the main technologies employed in this study to convert biomass into useful services is given. Table 12 summarizes the values of the energy efficiency as well as the costs considered for the calculations.

Table 12. Energy efficiencies and cost values used for the biomass to X technologies

Source	Product	Pathway	Conversion Factors (Energy)	CAPEX (CHF/kW)	OPEX (CHF/kW_{th}/y)
Wet Biomass	Biogas	Anaerobic Digestion	Wet Biomass: -2.86 Biogas : +1.00 (Pöschl, et al., 2010)	1053 (Ro, et al., 2006)	93.91 (Lantz, 2012)
Wet Biomass	BioSNG	Hydrothermal Gasification	Wet Biomass: -1.54 Electricity: +0.02 BioSNG : +1.00 (Gassner, et al., 2011)	1700 (Gassner, et al., 2011)	118.8 (Gassner, et al., 2011)

Wood	SNG, Heat, Electricity	SNG Gasification	Wood: -1.35 Electricity: 0.04 BioSNG: +1.00 $Heat_{LowT}$: 0.12 (Moret, 2017)	2930 (Moret, 2017)	149.44 (Moret, 2017)
Wet Biomass	Electricity	Anaerobic Digestion & ICE	Wet Biomass: -7.72 Electricity: +1.00 $Heat_{LowT}$: +1.29 (Pöschl, et al., 2010)	1776 (Ro, et al., 2006)	147.9 (Lantz, 2012)
Wood	Biodiesel	Fischer-Tropsch wet	Wood: -2.05 Electricity: -0.05 Biodiesel: +1.00 (Moret, 2017)	2360 (Moret, 2017)	40.16 (Moret, 2017)
Wood; Wet Biomass; NG	Biodiesel	Fischer-Tropsch dry	Wood: -2.25 Electricity: -0.03 Biodiesel: +1.00 $Heat_{LT}$:+0.39 (Moret, 2017)	1955 (Moret, 2017)	35.81 (Moret, 2017)
Plant	Gasoline	Plant-to-Ethanol (using parts of plants that are rich in cellulose)	Plant: - 3.57 Gasoline: +1.00 (Yao, et al., 2017)	2121 (Yao, et al., 2017)	546 (Yao, et al., 2017)
Plant	Jetfuel	Sugars-to-Jetfuel (Alcohol to Jet) (Sugars are e.g. corn, beet, sugarcane, wheat or similar waste that is rich in cellulose.)	Plant: - 3.30 Jetfuel: +1.00 (Qantas Airways Ltd., 2013) (Norden, 2016)	587.39 (Qantas Airways Ltd., 2013) (Norden, 2016)	75.04 (Qantas Airways Ltd., 2013) (Norden, 2016)
Wood; Wet biomass; Waste	Jetfuel	FT Synthesis	Wood: -0.78 Electricity: - 0.74 Jetfuel: +1.00 $Heat_{LowT}$: +0.30 (Hillestad et al., 2018)	6037.93 (Hillestad et al., 2018)	805.195 (Hillestad et al., 2018)
Wood	Biocrude, Electricity	Pyrolysis	Wood: - 1.5 Biocrude: +1.00 Electricity: +0.02 (Moret, 2017)	1435.49 (Moret, 2017)	71.77 (Moret, 2017)
Wood	Hydrogen	H_2 Gasification	Wood: -2.31 H_2: +1.00 (Moret, 2017)	2696.86 (Moret, 2017)	208.99 (Moret, 2017)
Waste, Electricity	Methanol, CO_2	RDF to Methanol	Waste: -2.39 Electricity: -0.05 Methanol: +1.00	3140.83 (Basile and Dalena, 2017)	551.33 (Basile and Dalena, 2017)
Wood, Electricity	Methanol, CO_2	Wood to Methanol	Dry Wood: -2.09 Electricity: -1.64 Methanol: +1.00	1606 (Bandi and Specht, 2004)	419.02 (Bandi and Specht, 2004)

4.1.1 Wood to Bio-Crude

Pyrolysis is a thermal cracking process for biomass processing that can deliver a number of products including gaseous, liquid and solid streams depending on the process design and the operating conditions. During pyrolysis, biomass is subjected to elevated temperatures in the absence of any oxidizing medium (i.e. inert atmosphere) resulting in a thermal breaking of the carbon matrix. The intensity of the carbon bond scission and thus, the physical state of the products is mostly dependent on the heating rate employed. Nowadays, the focus of pyrolysis however is the liquid bio-crude, produced when medium heating rates are used. Pyrolysis is often the first step in liquid biofuel production, as the output bio-crude requires an upgrading step prior to being used in fuel engines. Most pyrolysis processes employ fixed bed reactors and temperatures between 300 °C and 500 °C. According to (Moret, 2017) the process has an average of 1435.5 CHF/kW of equivalent bio-crude, while the operating costs are in the range of 71.77 CHF/kW. During pyrolysis, wood is converted to bio-crude with an energy efficiency of 0.66, while at the same time if energy recovery is used; a simultaneous power production is possible. The produced power is equivalent to 2% of the fuel product energy content.

4.1.2 Wood to Biomethane

Woody biomass can be converted to a gaseous fuel stream comprised mainly of CO and H_2 (syngas) and to a smaller extent CO_2 and CH_4 through gasification, a thermochemical process that employs biomass oxidation in sub-stoichiometric conditions to favour the production of CO instead of CO_2. Different oxidizing media such as steam, air or pure oxygen directly affect the product distribution in the outlet stream. Gasification is a mature technology that uses a plethora of different reactor configurations depending on the intended use of the produced syngas. Temperatures inside the gasifier can reach up to 700 °C and usually the heat is partially provided by combustion of a fraction of the product gas. A subsequent upgrade of the syngas with reaction with H2 results in enriching the product gaseous fuel in CH_4 as CO and CO_2 are converted into methane through the Sabatier reaction. Methanation is a catalytic conversion process that requires moderate temperatures (in the range of 250 °C to 350 °C) and pressures as high as 20-25 bars. As the reaction makes use of a catalyst to aid with the conversion, the latter usually being nickel or cobalt, it is evident that a cleaning step must precede in order to wash all impurities, sulphur and other hydrocarbons from the syngas. (Moret, 2017) reports an energy efficiency of wood to biomethane equal to 0.74. If heat recovery and turbines are used, an additional production of 12 % heat and 4 % power, with respect to the energy value of the product, can be achieved. The capital expenses for gasification to biomethane, according to the same source are 2930.11 CHF/kW while the operating costs are equal to 149.44 CHF/kW/y.

4.1.3 Wet Biomass to Biogas

Anaerobic digestion (AD) is a biochemical process that is used to break the biogenic carbon of wet biomass and release it in the form of biogas, a gaseous mixture of methane and carbon dioxide. Digestion of biomass under anaerobic conditions (absence or low concentrations of air) is realized with the aid of suitable bacteria and proceeds through a complex series of (bio-)chemical reactions that can be grouped in four main stages, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis. A set of parameters including the temperature and pH are decisive for the efficient operation of anaerobic digestion. In particular, three types of bacteria are used depending on the temperature of operation: thermophilic (45-55 °C), mesophilic (25-45 °C) and cryophilic (below 25 °C). The production of methane is directly linked with the nature of the employed bacteria and is positively affected by temperature; a direct compromise between methane production and energetic demands to sustain the operating temperature to levels above room temperature. Anaerobic digestion results also to a liquid by-product stream, the digestate, which contains all undigested biomass as well as the valuable nutrients originally in the feed stream (e.g. K, N, P etc.). Due to the latter, digestate streams are mostly used nowadays as soil fertilizers. However, the high carbon content of this residual stream leaves room for additional retrieval in the form of fuels by hydrothermal treatment.

The energy efficiency of anaerobic digestion greatly depends on both the nature of the digested biomass as well as the operating conditions. Together, they define the methane potential for each case (i.e. the produced volume of methane per mass unit of digestible matter). As the energetic content of methane is the only source of contained energy in the output biogas stream, the methane potential is a crucial parameter to define the energy efficiency of the process. Overall efficiencies range from 0.1 to 0.4 in the literature depending on the plant size and raw material, with a mean value of 0.37 given by (Thees, et al., 2017) for animal manure.

According to (Lantz, 2012), the investment cost of a 0.4 MW (3540 MWh/y) biogas unit under thermophilic conditions amounts to 370'000 EUR. This corresponds to 915.6 EUR/kW or 1053 CHF/kW. Similarly, the operating costs excluding the transport of biomass to the processing unit can be calculated from the same reference as 81.66 EUR/kW/y or 93.91 CHF/kW/y.

Biogas produced from anaerobic digestion can be sent to an upgrading unit to separate CO_2 and thus, enrich the calorific value of the fuel by concentrating the biomethane content or simply sent to combustion engines for electricity production with potential heat recovery. In this study, a spark ignition (SI) engine was considered with an electrical efficiency of 0.37 and a thermal efficiency of 0.45. The values of the combined system are listed in Table 12.

4.1.4 Wet Biomass to Biomethane

Hydrothermal gasification (HTG) offers the possibility of converting wet organic streams into methane using high pressure to reach supercritical water conditions in a complex reactor scheme. Compared to traditional gasification, it offers the advantage that it utilizes the wet stream as it is, avoiding the preceding energy intensive drying step. Moreover, water in its supercritical condition has low density and dielectric constant. Consequently, it changes from polar to non-polar solvent and thus, the organic compounds dissolve easily in it. Furthermore, the supercritical conditions that prevail within the HTG reactor also ensure that the nitrous and phosphoric minerals contained in some forms of wet biomass such as sewage sludge and manure are released unharmed in the residual output stream. Apart from direct processing of wet biomass streams, HTG can be used to convert the lignin-rich digestates from anaerobic digestion. On the drawbacks of the process stand the energy needed to reach the operating conditions (around the critical point of water, i.e. 370 K and 220 bars) as well as the use of a catalyst, which in turn requires special attention with regard to maintenance (poisoning prevention, degradation handling etc.)

According to (Gassner, et al., 2011), a mean energy efficiency for various wet biomass types is around 0.60 with a simultaneous electrical efficiency of 0.04, especially if power recovery from the high pressure vapour phase is considered. From the same reference, a maximum capital investment for this level of energy efficiency was in the range of 1'700 CHF/kW, observed for manure samples but without considering catalyst deactivation costs for a 20 MW plant. The operating costs for the same plant are calculated to be 118.8 CHF/kW/y, again without considering the deactivation of the catalyst.

4.1.5 Biomass to alcohols

Primary alcohols such as methanol and ethanol are not only individually used fuels but also constitute chemicals used as the basis for synthesis of higher fuels, as for example aviation fuels. Alcohols can be produced from both woody or non-woody biomass using different conversion pathways. Methanol can be produced from wood gasification followed by a synthesis step to convert the produced syngas. According to (Bandi, et al., 2004), the capital expenses of a 145 MW equivalent methanol plant amount to 203 million Euros, roughly 1600 CHF/kW methanol. The corresponding operating expenses are 419 CHF/kW/y. The plant utilizes 1.64 kW of electrical power per kW of produced methanol and converts wood with a total efficiency of 0.478.

Ethanol is primarily produced via the biochemical fermentation of biomass crops such as corn, wheat or sugarcane. Fermentation is usually preceded by pretreatment and handling steps like milling and hydrolysis which aims to isolate the sugars from the biomass matrix. Then the biological degradation step is able to transform the sugars in chemicals of fuels such as ethanol depending on the design of the process. According to (Yao, et al., 2017) the economics of a 4000 bpd (196 MW equivalent) plant consist of a capital investment of 2121 CHF/kW and operating costs of 546 CHF/kW/y.

Accordringly, organic waste can be converted into valuable chemicals such as methanol. According to (Basile, et al., 2017) who give the values for a 300 t/d methanol production plant from RDF, the capital costs are 3141 CHF/kW while the operating costs are approximately 551 CHF/kW/y.

4.1.6 Biomass to synthetic liquid biofuels

The Fischer-Tropsch (FT) reaction, first developed by Franz Fischer and Hans Tropsch in the 1920s, is a catalytic synthesis process realized as a polymerization of carbon atoms. It is mainly used to produce synthetic biofuels from gasification-derived syngas. The chemical reaction is described by a simple representation of the form:

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

where *n* is the number of carbon atoms in the polymer chain. The conversion conditions (around 200-300 ºC and pressure in the range of tens of bars) are used to inhibit the formation of small alkanes but rather push towards the production of long chain hydrocarbons with carbon chains of 10-20 atoms, according to the Anderson-Schulz-Flory (ASF) distribution. The FT process uses catalysts to promote the growth of the carbon chain, with nickel or cobalt being the most commonly used ones. However, their low poisoning resistance to sulphuric derivatives dictates stringent syngas cleaning steps prior to insertion in the FT reactor. The produced hydrocarbon blend must then undergo hydrotreatment in order to obtain the desired biofuel quality. The addition of hydrogen in a subsequent hydrocracking reactor leads to the chemical cleavage of the long-chain hydrocarbons and under controlled conditions, the acquisition of a paraffin blend (biodiesel) of desired quality.

The energetic efficiency of the FT process according to (Moret, 2017) is in the order of 0.45 with a simultaneous heat recovery of 0.39 kW per kW equivalent biodiesel. The capital investment for a 30 MW installation amounts to 1955 CHF/kW, while the operating costs are 35.81 CHF/kW/y.

4.2 Carbon Dioxide to X

An interesting alternative to the use of carbon, either fossil or biogenic, for fuel production is the use of carbon dioxide from direct air capture or industrial sites as carbon sources.

Different technologies are used for different volume fractions of carbon dioxide in flue gases or in the air, which influences the costs of carbon capture (CC). Carbon dioxide in air has to be captured and separated by carbon capture technologies in order to have a more concentrated and thereby usable carbon source. Gases produced in biogas and sewage-treatment plants consist of one-third carbon dioxide and can thus be fed directly into e.g. a biological methanation plant in order to convert the remaining carbon dioxide into methane as well.

For all carbon capture and utilization (CCU) technologies, the conversion efficiency and therefore the overall product depends on the carbon dioxide source. If pure carbon dioxide is used as a feed, higher efficiencies can be reached. The acquisition of pure carbon dioxide from air or industrial sources is described in Section 4.3 If industrial flue gas is used directly for the production of carbon based synthetic fuels or products, then these technologies will be treated in the current chapter.

The EU project CarbonNext (www.carbonnext.eu) provides a list of selected pathways from carbon dioxide to products. Combined with further pathways, the following conversion processes are defined:

Table 13. Summary of carbon dioxide to X technologies considered.

Product	Pathway	TRL	Conversion Factors	CAPEX (CHF/kW)	Maintenance (CHF/kW$_{th}$/y)
Ethylene	Methanol to olefin (MTO) process (condensation of CO_2-derived methanol to DME followed by conversion to olefin)	8-9 (CarbonNext, 2017)	H_2: - 0.71 kWh Methanol: - 2.52 kWh CO_2: - 0.24 kg Ethylene: + 1.00 kWh (CarbonNext, 2017)	45.70 (CarbonNext, 2017)	2.29 (= 5%)
Propylene	Methanol to olefin (MTO) process (methanol plus ethylene)	8-9 (CarbonNext, 2017)	H_2: - 0.26 kWh Methanol: - 2.60 kWh CO_2: - 0.25 kg Ethylene: +1.00 kWh Propylene: +1.00 kWh (CarbonNext, 2017)	47.11 (CarbonNext, 2017)	2.36 (= 5%)
Propylene	Methanol to olefin (MTO) process (condensation of CO_2-derived methanol to DME followed by conversion to olefin)	8-9 (CarbonNext, 2017)	H_2: - 0.73 kWh Methanol:-2.60 kWh CO_2: - 0.25 kg Propylene: +1.00 kWh	47.11 (CarbonNext, 2017)	2.36 (= 5%)
Benzene	Methanol to aromatics (MTA)	7	H_2: - 0.93 kWh Methanol: - 0.89 kWh	53.69	2.68

	process developed by Mobil involving reacting methanol over a zeolite catalyst resulting in the simultaneous production of all three BTX components.	(CarbonNext, 2017)	CO_2: - 0.30 kg Benzene: +1.00 kWh (CarbonNext, 2017)	(CarbonNext, 2017)	(= 5%)
Xylene	Methanol to aromatics (MTA) process developed by Mobil involving reacting methanol over a zeolite catalyst resulting in the simultaneous production of all three BTX components.	7 (CarbonNext, 2017)	H_2: - 0.88 kWh Methanol: - 0.87 kWh CO_2: - 0.29 kg Xylene: +1.00 kWh (CarbonNext, 2017)	52.65 (CarbonNext, 2017)	2.63 (= 5%)
Dimethyl ether	Condensation then dehydration of CO_2 derived methanol in the presence of a solid acid catalyst	9 (CarbonNext, 2017)	H_2: - 0.71 kWh Methanol: -0.69 kWh CO_2: - 0.24 kg Dimethyl ether: +1.00 kWh (CarbonNext, 2017)	23.7 (CarbonNext, 2017)	1.18 (= 5%)
Acetic Acid	Cativa Carbonylation		Methanol: -1.40 Acetic Acid: +1.00	891.0 (Towler, et al., 2012)	44.55 (= 5%)
Acetic Acid	Hydro Carbonylation		Methanol: -1.43 Acetic Acid: +1.00	710.9 (Towler, et al., 2012)	35.55 (= 5%)
Methanol	Reverse water gas shift of CO_2 and renewable H2 to produce CO and water, remove water, add more H_2, then use F-T reactions to produce methanol.	7-9 (CarbonNext, 2017)	H_2: - 1.50 kWh CO_2: - 0.50 kg Methanol: +1.00 kWh (CarbonNext, 2017)	64.9 (CarbonNext, 2017)	3.25 (= 5%)
Methanol	CO_2/steam reforming of CH_4, followed by water gas shift reaction to adjust the CO:H_2	5-7 (CarbonNext, 2017)	NG: - 0.40 kWh CO_2: - 0.25 kg Methanol: +1.00 kWh (CarbonNext, 2017)	284.8 (CarbonNext, 2017)	14.24 (= 5%)

	ratio, water removal, compression and subsequent methanol synthesis via F-T.				
Methanol	Dry reforming of CH_4 and CO_2 to produce syngas, followed by water gas shift reaction to adjust the CO:H_2 ratio, water removal, compression and subsequent methanol synthesis via F-T.	6-7 (CarbonNext, 2017)	Methane: -0.08 kWh CO_2: - 0.25 kg Methanol: + 1.00 kWh (CarbonNext, 2017)	269 (CarbonNext, 2017)	13.43 (= 5%)
Methanol	High temperature solid oxide cells use CO_2 and water to produce H_2 and CO, followed by compression and subsequent catalytic methanol synthesis.	3-5 (CarbonNext, 2017)	CO_2: - 0.25 kg Methanol: + 1.00 kWh (CarbonNext, 2017)	406 (CarbonNext, 2017)	20.28 (= 5%)
Methanol	Two-step process, first convert CO_2 to CH_4 via Sabatier reaction, then partially oxidize CH_4 to CH_3OH	2-4 (CarbonNext, 2017)	H_2: - 1.5 kWh CO_2: - 0.25 kg Methanol: + 1.00 kWh (CarbonNext, 2017)	34 (CarbonNext, 2017)	1.71 (= 5%)
Gasoline	Gas fermentation of syngas produced from CO2 by the anaerobic bacterium Clostridium autoethanogenum.	2-4 (CarbonNext, 2017)	H_2: - 0.88 kWh CO_2: - 0.26 kg Gasoline: + 1.00 kWh (CarbonNext, 2017)	68.64 (CarbonNext, 2017)	3.43 (= 5%)
Gasoline	Syngas produced from CO_2 and H_2 undergoes F-T reactions to produce gasoline-range hydrocarbons	7-8 (CarbonNext, 2017)	H_2: - 1.97 kWh CO_2: - 0.42 kg Gasoline: + 1.00 kWh	205.9 (CarbonNext, 2017)	10.30 (= 5%)

Gasoline	Methanol to Gasoline process, via DME and olefins	6-8 (CarbonNext, 2017)	H_2: - 1.35 kWh CO_2: - 0.42 kg Methanol: - 7.99 kWh Gasoline: +1.00 kWh (CarbonNext, 2017)	80.8 (CarbonNext, 2017)	4.04 (= 5%)
Diesel	Syngas produced from CO_2 and H_2 undergoes F-T reactions to produce linear waxes. Hydrocracking converts to synthetic diesel	7-8 (CarbonNext, 2017)	H_2: - 1.19 kWh CO_2: - 0.26 kg Diesel: + 1.00 kWh (CarbonNext, 2017)	126.7 (CarbonNext, 2017)	6.33 (= 5%)
Jet fuel	Jet fuel produced via methanol pathway, with carbon dioxide from direct air capture.		Electricity: -2.62 kWh Jet fuel: +1.00 kWh (Schmidt, et al., 2018) CO_2:- 0.26 kg (CarbonNext, 2017)	4130 (Schmidt, et al., 2018)	206.50 (= 5%)
Jet fuel	Jet fuel produced via Fischer-Tropsch pathway, with carbon dioxide from direct air capture.		Electricity: -2.61 kWh Jet fuel: +1.00 kWh (Schmidt, et al., 2018) CO_2:- 0.26 kg (CarbonNext, 2017)	5340 (Schmidt, et al., 2018)	267.00 (= 5%)
Jet fuel	Jet fuel produced via methanol pathway, with carbon dioxide from concentrated source.		Electricity: -2.07 kWh Jet fuel: +1.00 kWh (Schmidt, et al., 2018) CO_2:- 0.26 kg (CarbonNext, 2017)	2280 (Schmidt, et al., 2018)	114.00 (= 5%)
Jet fuel	Jet fuel produced via Fischer-Tropsch pathway, with carbon dioxide from concentrated source.		Electricity: -2.14 kWh Jet fuel: +1.00 kWh (Schmidt, et al., 2018) CO_2:- 0.26 kg (CarbonNext, 2017)	3420 (Schmidt, et al., 2018)	171.00 (= 5%)
Methane	Methanation	6-7 (CarbonNext, 2017)	H_2: - 1.20 kWh CO_2: - 0.20 kg NG: +1.00 kWh (CarbonNext, 2017)	2633.0	131.65 (= 5%)
LNG	Power to liquefied gas		Electricity: -1.26 kWh LNG: +1.00 kWh (Moret, 2017)	190 (Moret, 2017)	9.50 (= 5%)

In the following sections, some of the most important technologies for converting CO_2 to fuels and chemicals are presented.

4.2.1 Carbon Dioxide to Methanol

In Iceland, the company "Carbon Recycling International (CRI)" develops, engineers, builds and operates Emissions-to-Liquids methanol production plants. Their standard Emissions-to-Liquids plant design has a methanol production capacity of 50'000 tons per year. (Ausfelder et al., 2015) defines a conversion efficiency of 88% for the above chemical reaction with regard to the lower calorific values and a lifetime of the plant of >20 years. In their white paper (Wagemann et al., 2017), DECHEMA writes that 1 TWh power yields 200 Mio. m^3 hydrogen, from which around 90'000 tons methanol is produced. The SCCER White Paper (Kober et al., 2019) reports a CAPEX of a Methanol synthesis reactor of 120 – 310 CHF/kW_{th}.

4.2.2 Carbon Dioxide to Methane

The current economy is largely based on natural gas, with is a gas mixture of primarily methane. To replace fossil with renewable gas, the conversion of hydrogen with carbon dioxide to methane is a promising path. There are two types of methanation reactors: Biological methanation and catalytic thermochemical methanation. Methanation consists mainly of three reactions:

Methanation reaction: $CO + 3H_2 \rightarrow CH_4 + H_2O$

Reverse water-gas shift reaction: $CO_2 + H_2 \rightarrow CO + H_2O$

Sabatier reaction: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Methanation is the reverse of methane steam forming, which is currently the most important technique to produce hydrogen (Van Leeuwen et al., 2018).

Biological methanation is a promising new technology to convert carbon dioxide and hydrogen into methane. Leading in this field is the Germany-based company Electrochaea. Their system "BioCat" is scalable, currently they offer plant sizes with outputs between 50 Nm^3/h CH_4 and 500 Nm^3/h CH_4.

Figure 3 presents a schematic representation of the process.

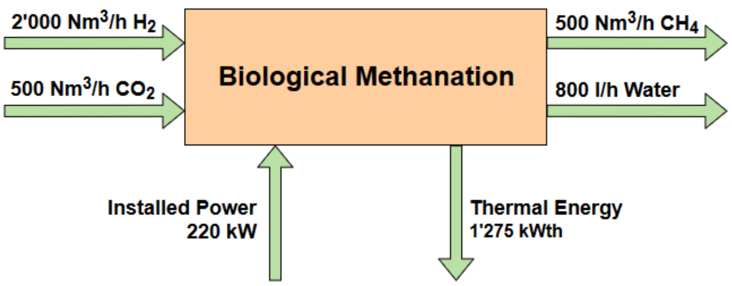

Figure 3. Specification of a biological methanation based on Electrochaea's BioCat methanation plant. Reactor temperature is 63 °C, reactor pressure is 10 barg.

The efficiencies of such a biological methanation reactor is <99%, with an energy conversion efficiency (H_2 to CH_4) of <74%. The total system energy conversion efficiency is between 52% and 58% (Electrochaea, 2018).

In general, the conversion rates of biological and catalytic methanation are very similar. The main difference lies in the electrical and thermal energy flows. Electrical energy input is needed for the stirring unit in the biological methanation plant, and for the cooling circuit in catalytic methanation. Both methanation processes are exothermic with usable thermal energy. While the temperature of a biological methanation is slightly above 60°C, the catalytic reactor works on a higher temperature level of about 300°C.

The Store&Go project has carried out a large literature study for chemical as well as biological methanation (Van Leeuwen et al., 2018). They summarize their findings as follows:

Table 14. Base case assumptions and ranges for costs parameters of methanation reactors (Van Leeuwen et al., 2018).

	Catalytic Methanation	Biological Methanation
CAPEX methanation reactor (€/kW$_{SNG}$)	400 (110 – 1500)	550 (100 - 1500)
OPEX (% of CAPEX)	10%	10%
Lifetime (years)	20	20
Energetic efficiency (% HHV)	77.9	77.9

4.2.3 Carbon Dioxide to LNG

(Morosanu, et al., 2018) take a closer look at the LNG (liquefied natural gas) production from carbon dioxide and hydrogen. According to their calculations, 3.6 kg of H_2 combined with 20 kg carbon dioxide yield in 7.2 kg LNG and a heat production of 22.3 kW$_{th}$. Or in terms of energy, 120 kWh hydrogen and 20 kg carbon dioxide lead to 90 kWh LNG and 22.3 kWh heat.

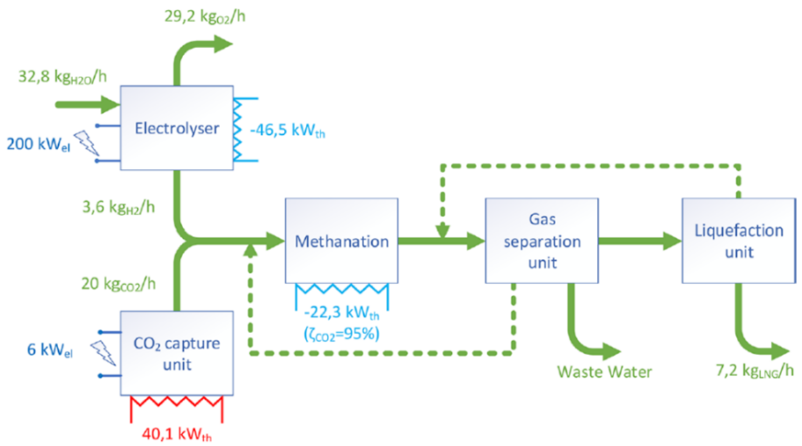

Figure 2. Block flow diagram with preliminary mass and energy balance for the conversion of carbon dioxide (from air) and hydrogen to LNG (Morosanu, et al., 2018).

The LNG module itself converts 126.2 kWh of methane into 112.5 kWh LNG and needs an extra electricity input of 4.1 kWh.

4.2.4 Carbon Dioxide to Jet Fuel

In the past decade, there has been research in the field of renewable jet fuel production all over the planet - from norden and SINTEF in Scandinavia to the Centre for Low Carbon Futures in the UK or Qantas in Australia. Several studies were also published by ”Air Transport Action Group” (ATAG), which is a non-profit association that represents all sectors of the air transport industry and is situated in Geneva, Switzerland. Most of these studies cover the renewable production pathways of jet fuels from biomass. Only the report by the ”Centre for Low Carbon Future” looks at a conversion technology using air and water as feedstock for carbon dioxide and hydrogen. This document gives an overview on the outcomes of the different studies and conversion pathways.

IATA published a fact sheet in June 2018 (IATA, 2018) and defined their strategy concerning sustainable alternative jet fuels in (IATA, 2018). In their strategy paper they claim that IATA member airlines committed to the following goals:

- Fuel efficiency improvement of 1.5% per year on average between 2009 and 2020.
- Carbon-neutral growth from 2020.
- 50% net emissions reduction in 2050 compared to 2005

There are several terms for jet fuels produced from renewable sources, such as renewable aviation fuel, renewable jet fuel, alternative fuel, biojet fuel, aviation biofuel and sustainable alternative fuel. ’Biofuels’ generally refers to oil produced from biological resources (plant or animal material). However, current technology allows fuel to be produced from other alternative sources, including non-biological resources. In this study, the term “sustainable alternative jet fuel” (SAF) is introduced, which incorporates all technologies.

(Schmidt, et al., 2018) defines two current technologies to produce jet fuels from carbon dioxide: the methanol pathway or Fischer-Tropsch. In their paper they look at the techno-economic performance of both pathways for today and for the year 2050, considering direct air capture as well as concentrated sources as carbon sources for both technologies.

Using direct air capture, the following conversion efficiencies were defined for the two technologies:

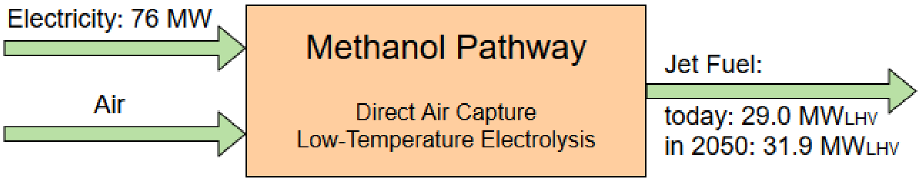

Figure 5. Block flow diagram with preliminary mass and energy balance for the conversion of carbon dioxide from air to jet fuel, via the methanol pathway with direct air capture and low-temperature electrolysis. Output values: today and forecast for 2050 (Schmidt, et al., 2018).

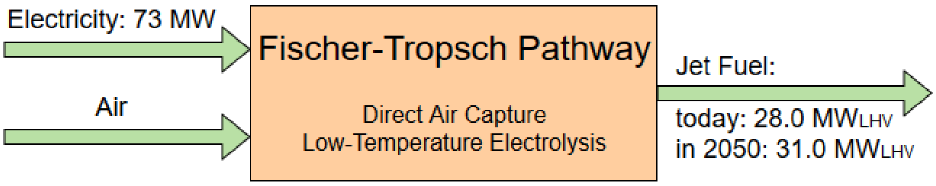

Figure 6. Block flow diagram with preliminary mass and energy balance for the conversion of carbon dioxide from air to jet fuel, via the Fischer-Tropsch pathway with direct air capture and low-temperature electrolysis. Output values: today and forecast for 2050 (Schmidt et al., 2018).

Next to the direct air capture, (Schmidt et al., 2018) also considered the use of more concentrated carbon dioxide sources (e.g. from industrial flue gases). Carbon capture from direct air has to handle very low carbon dioxide concentrations. For this reason, the use of concentrated sources is cheaper (and more developed).

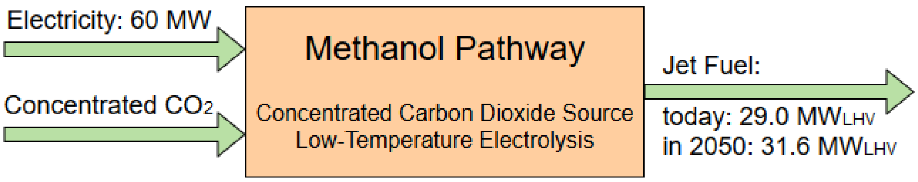

Figure 7. Block flow diagram with preliminary mass and energy balance for the conversion of carbon dioxide from a concentrated CO_2 source to jet fuel, via the Methanol pathway with low-temperature electrolysis. Output values: today and forecast for 2050 (Schmidt et al., 2018)

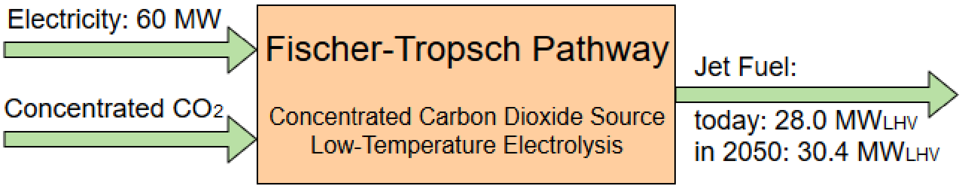

Figure 8. Block flow diagram with preliminary mass and energy balance for the conversion of carbon dioxide from a concentrated CO_2 source to jet fuel, via the Fischer-Tropsch pathway with low-temperature electrolysis. Output values: today and forecast for 2050. (Schmidt et al., 2018)

Next to the conversion rates, (Schmidt et al., 2018) define the cost and efficiency parameters as well. For the two pathways in combination with low-temperature electrolysis, they found the following values presented in Table 15 below:

Table 15. Parameters of jet fuel production for both methanol and Fischer-Tropsch pathways, combined with low-temperature electrolysis. Currency conversion: 1 € = 1.14 CHF.

	Methanol pathway		Fischer-Tropsch pathway	
	Direct Air Capture	Concentrated Source	Direct Air Capture	Concentrated Source
Efficiency	today: 39% 2050: 42%	today: 48% 2050: 54%	today: 39% 2050: 42%	today: 47% 2050: 53%
CAPEX ($kCHF/kW_{fuel}$)	today: 4.13 2050: 2.15	today: 2.28 2050: 1.03	today: 5.34 2050: 2.29	today: 3.42 2050: 1.13
OPEX (CHF/GJ_{LHV})	today: 108.3 2050: 45.4	today: 80.9 2050: 31.9	today: 111.4 2050: 48.7	today: 85.7 2050: 35.7
OPEX (CHF/kWh_{th})	today: 0.390 2050: 0.163	today: 0.291 2050: 0.115	today: 0.401 2050: 0.175	today: 0.309 2050: 0.129
Sensitivity	today: -28%,+4.1% 2050: -44%,+4.9%	today: -30%,+5.5% 2050: -43%,+7.0%	today: -27%,+4.0% 2050: -41%,+4.6%	today: -28%,+5.2% 2050: -39%,+6.2%

These values are used for implementation into the model. (Schmidt et al., 2018) included high-temperature electrolysis as well in their paper. However, for reasons of simplification and because high-temperature electrolysis is not fully developed yet, these pathways are not regarded in the current study.

4.3 Other Conversion Technologies

Table 16 lists the rest of the conversion technologies used in the model. They mainly cover the synthesis of biochemicals and bioplastics from carbon sources, as well as the provision of the necessary hydrogen source through electrolysis. It should be noted that in contrast to the technologies presented above, the conversion efficiency accounting to chemical and plastic synthesis technologies is reported in terms of mass and not energy.

Table 16. Summary of other technologies considered.

Resource	Product	Pathway	Conversion efficiency	CAPEX (CHF/kW)	OPEX ($CHF/kW_{th}/y$)
Ethanol	Jet Fuel	Alcohol to Jetfuel (ATJ)	Ethanol: -1.00 Jetfuel: +1.00 (Yao, et al., 2017)	727.50 (Yao, et al., 2017)	68.81 (Yao, et al., 2017)
LNG	Electricity	Liquid-to-Power	LNG: -1.41 Electricity: +1.00 (Moret, 2017)	0.00 (Moret, 2017)	0.00 (Moret, 2017)
Electricity	Electricity	Power-to-Power (Storage)	Electricity: 1.00 (Moret, 2017)	3118.41 (Moret, 2017)	155.92 (Moret, 2017)
Electricity	Hydrogen	Alkaline Electrolysis	Electricity: -1.72 Hydrogen: +1.00	1345	47

			$Heat_{LowT}$: +0.26 (Van Leeuwen, et al., 2018)	(Van Leeuwen, et al., 2018)	(Van Leeuwen, et al., 2018)
Electricity	Hydrogen	PEM Electrolysis	Electricity: -1.43 Hydrogen: +1.00 $Heat_{LowT}$: +0.26 (Van Leeuwen, et al., 2018)	1870 (Van Leeuwen, et al., 2018)	66 (Van Leeuwen, et al., 2018)
Electricity	Hydrogen	Electrolysis	Electricity: -1.18 Hydrogen: +1.00 (Moret, 2017)	328.47 (Moret, 2017)	32.85 (Moret, 2017)
NG	Hydrogen	Reforming	NG: -1.36 Hydrogen: +1.00 (Moret, 2017)	727.5 (Moret, 2017)	68.81 (Moret, 2017)
Ethane, Oxygen	Acetic Acid	Ethane Oxidation	Ethane: -1.43 Ethylene: +1.00 Acetic Acid: +0.29 (Smejkal, et al., 2005)	860 (Smejkal, et al., 2005)	368 (Soliman, et al., 2012) (Smejkal, et al., 2005)
Benzene, Propylene	Phenol, Acetone	Cumene Process	Benzene: -3.00 Propylene: -0.95 Acetone: +1.00 Phenol: +0.92 Acetic Acid: +0.01 (Aspen, 2018)	733 (Towler, et al., 2012)	0.0042 (Towler, et al., 2012)
Ethane	Ethylene	Ethane Cracking	Ethane: -1.49 Ethylene: +1.00 (van Goethem, et al., 2013)	1710 (Towler, et al., 2012)	0.0098 (Towler, et al., 2012)
Methanol	Ethylene	Methanol-to-Olefins	Methanol:-4.04 Propylene. +1.00 Ethylene: +0.55	1542 (Towler, et al., 2012)	0.0088 (Towler, et al., 2012)
Ethane, Propane	Ethylene	Ethane Propane Cracking	Ethane: -1.58 Ethylene: +1.00 Propylene: +0.22	1066 (Towler, et al., 2012)	0.0061 (Towler, et al., 2012)
Propane	Propylene	Oleflex Process	Methanol: -3.47 Propylene: +1.00 Ethylene: +0.33	796 (Towler, et al., 2012)	0.0045 (Towler, et al., 2012)
Ethylene, Butane	Propylene	Metathesis Propylene	Ethylene: -1.10 Propylene: +1.00 (Dukandar, 2014)	523 (Towler, et al., 2012)	0.0030 (Towler, et al., 2012)

5 Model

For modelling and optimizing the carbon flows in Switzerland, this project works with EnergyScope, an energy-based modelling tool developed by the EPFL (École Polytechnique Fédérale de Lausanne). According to (Moret, 2017), an energy-based modelling framework is often formulated as MILP (Mixed Integer Linear Programming) problem, which is also the case for EnergyScope.

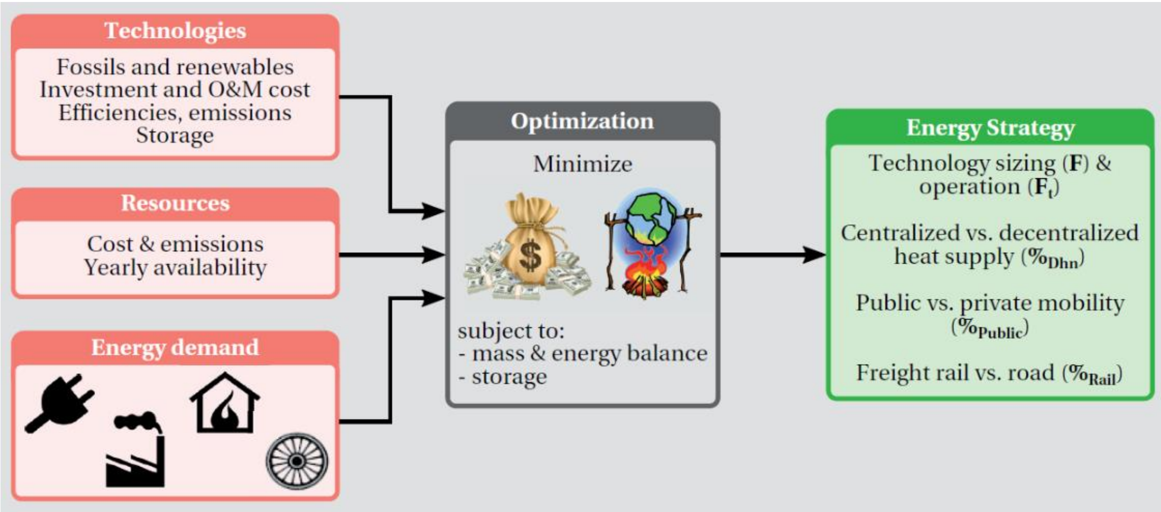

Figure 9. Overview of the MILP modeling framework of EnergyScope (Moret, 2017).

The figure above illustrates the conceptual structure of the original EnergyScope model. Given the end-use energy and product demand, the efficiency and the cost of energy conversion technologies, the availability and cost of energy sources, the model identifies the optimal investment and operation strategies to meet the demand and minimize the total annual cost or GHG emissions of the system. This identification is achieved as part of an optimization problem targeted at the minimization of the total system cost or the global warming potential. The end result is the definition of the various interacting paths from resources to products which in turn define the optimal energy strategy given the constraints and objectives of the energy system.
An energy system is a collection of conversion processes that are used to transform the available resources and deliver the end use products to the consumers. The developed modelling framework constitutes the methodology used to apply the model of the energy system. EnergyScope is an energy planning tool, in the sense that it provides an interaction between users and the model as the users can configure the inputs depending on the question they want to answer. Snapshot models are used to evaluate the energy system configuration and operation over a specified timespan.

5.1 EnergyScope

EnergyScope is designed to support decision-makers by improving their understanding of the energy system. The goal is to show the effect of the policy and investment decisions on final energy consumption, total cost and environmental impact. The model has a monthly resolution to highlight seasonality issues. It is a tool whose targeted users are not specialists of the energy domain, giving special attention to the ease-of-use of the tool and the low computation time of the model. (Codina Gironès et al., 2015) give a detailed overview and explanation of EnergyScope.

The quality of the modelling approach is directly proportional to the degree of simplification that is possible to achieve. Key challenges to face in this regard are the choice of the level of detail, the identification of the key variables impacting the system, the definition of the model structure, the distinction between the demand and supply, the inclusion of technologies producing or requiring both heat and electricity (e.g. heat pumps and cogeneration).

5.1.1 Modelling approach

The modelling approach consists of the definition of the key methodological assumptions, inputs and outputs of the model, the model structure, information and data flow. The classical representation of a country's final energy consumption as the sum of the four main sectors (households, services, industry, transportations) is replaced by a tripartition into electricity, heating and transportation. This distribution has the advantage of highlighting the competition between electricity and fuels for heating and transportation end-uses.

A distinction is introduced between modelling demand and supply. Energy demand modelling concerns the definition of the end-uses, i.e. the requirements in energy services (e.g. mobility, heating, etc.) Energy supply modelling concerns the choice of the energy conversion technologies to supply these services, and it is therefore related to the final energy consumption. Based on the technology choice, the same end-use energy requirement can be satisfied by a different final energy consumption, depending on the efficiency of the chosen energy conversion technology. In the present methodology this distinction is also made clear in the input categories in such a way that generic and efficiency inputs influence demand modelling, while the other inputs affect only the supply side. This allows decision-makers to understand that actions can be taken on both the supply and demand sides of the energy system.

5.1.2 Model description

The model falls into the "snapshot" category and is able to evaluate different energy system configurations for a target year (2035 or 2050). The time horizon is one year divided into 12 time steps which represent the months. The use of time steps rather than time-slices allows the implementation of technologies for electricity storage.

EnergyScope covers the demand in the mobility, transport, heating, cogeneration, and electricity sectors, including most common technologies that fulfil these requirements. Therefore, these sectors will not be further described here, as (Codina Gironès et al., 2015) describe the model in detail in their paper.

5.1.3 MILP – Mixed Integer Linear Programming

The core of EnergyScope a mixed integer linear programming optimization problem. Linear programming is used to maximize (or minimize) a linear objective function subject to one or more constraints (equalities and/or inequalities). Mixed integer programming adds one additional condition that at least one of the variables can only take on integer values. The formulation is particularly useful for problems where the existence of a constraint (or a set of constraints) is subject to the optimization algorithm. In the case of EnergyScope, the MILP formulation permits the consideration of the existence of the conversion technologies that bridge the paths from resources to products to be optimization variables.

Linear programming is especially useful as it is able to solve complex problems. However, it can only be brought into account, if linear expressions or approximations are used. While a linear dependence between the problem variables is not often the case, the approximation will eventually lead to uncertainties in the results. Another aspect of linearization is that the approximated functions are sensitive to changes in the problem variables. It is however a fitting solution to quickly obtain results within acceptable tolerance limits. Finally, limiting the range of the problem by adding further constraints can also limit the possible solutions that are given in the problem by guiding the optimization algorithm and may act as a factor that facilitates the acquisition of a useful set of solutions.

5.2 Carbon Flows Model

For optimizing carbon flows in Switzerland, the EnergyScope model is complemented by further technologies and demand in products and organic chemicals as described in Sections 6.1, 6.2 and 6.3. In order to use more domestic carbon sources, biomass technologies and Power-to-X technologies are included, as well as the corresponding necessary sources. Figure 10 shows the technologies, sources and layers that are already implemented in the EnergyScope or added in this project.

This part is built up in the project and, once established, can be used as framework that doesn't need to be changed anymore. In the scenario analysis, the user changes only the boundary conditions that are to be evaluated. Examples for this are a change in the availability of fossil fuels, or an increase in the import price of them, or the enforced or prohibited use of a certain technology, or a change in the demand sectors.

The model calculates the carbon flows considering the overall energy balance. As the energy content of carbon dioxide is negligible and the amount of available CO_2 more or less unlimited (at least in the atmosphere), the energy amount that is needed to extract pure carbon dioxide is used for representing the energy flow of carbon dioxide.

For each technology, the following parameters are defined:

Table 17. Parameters assigned to each conversion technology.

Parameter	Units	Description
c_{inv}	CHF/kW	Technology specific investment cost
c_{maint}	CHF/kW$_{th}$/y	Technology specific annual O&M cost
c_p	-	Annual capacity factor
f_{max}	GW	Maximum installed size of the technology
$f_{max\text{-}perc}$	-	Maximum relative share of a technology in a layer
f_{min}	GW	Minimum installed size of the technology
$f_{min\text{-}perc}$	-	Minimum relative share of a technology in a layer
gwp_{constr}	kgCO$_{2\text{-eq.}}$/kWh$_{th}$	Technology construction specific GHG emissions
ref_{size}	GW	Reference plant size (energy output)

One constraint is, as mentioned before, the linearity of the model. It is therefore highly sensitive to changes in data.

In order to be able to quantify and track the carbon flows in the energy system, the definition of the carbon content of the energy streams was used. The carbon content refers to the amount (mass) of carbon contained in an energy stream and is calculated as follows:

$$Carbon\ content\ = \frac{C\ mass\ fraction}{LHV}\ \left[\frac{kt}{GWh}\right]$$

Table 18 lists the carbon content of the main carbon containing resources

Table 18. Carbon content of the resources and products used in this study.

Resource	*C mass fraction (kg C / kg)*	*LHV (kWh / kg)*	*Carbon content (kt C / GWh)*
Gasoline	0.83	12.06	0.0688
Diesel	0.861	11.83	0.0728
Wood	0.50	4.50	0.111
Natural Gas	0.704	13.10	0.0537
Coal	0.90	8.00	0.1125
Waste	0.40	2.71	0.1476
Wet Biomass	0.40	3.90	0.1025
Bioethanol	0.522	8.25	0.0633
Biodiesel	0.861	11.83	0.0727
LFO	0.855	12.22	0.0699
LNG	0.704	15.33	0.0459
Biogas	0.44	5.31	0.0828

The technologies employed in this study are schematically depicted in Figure 10 below:

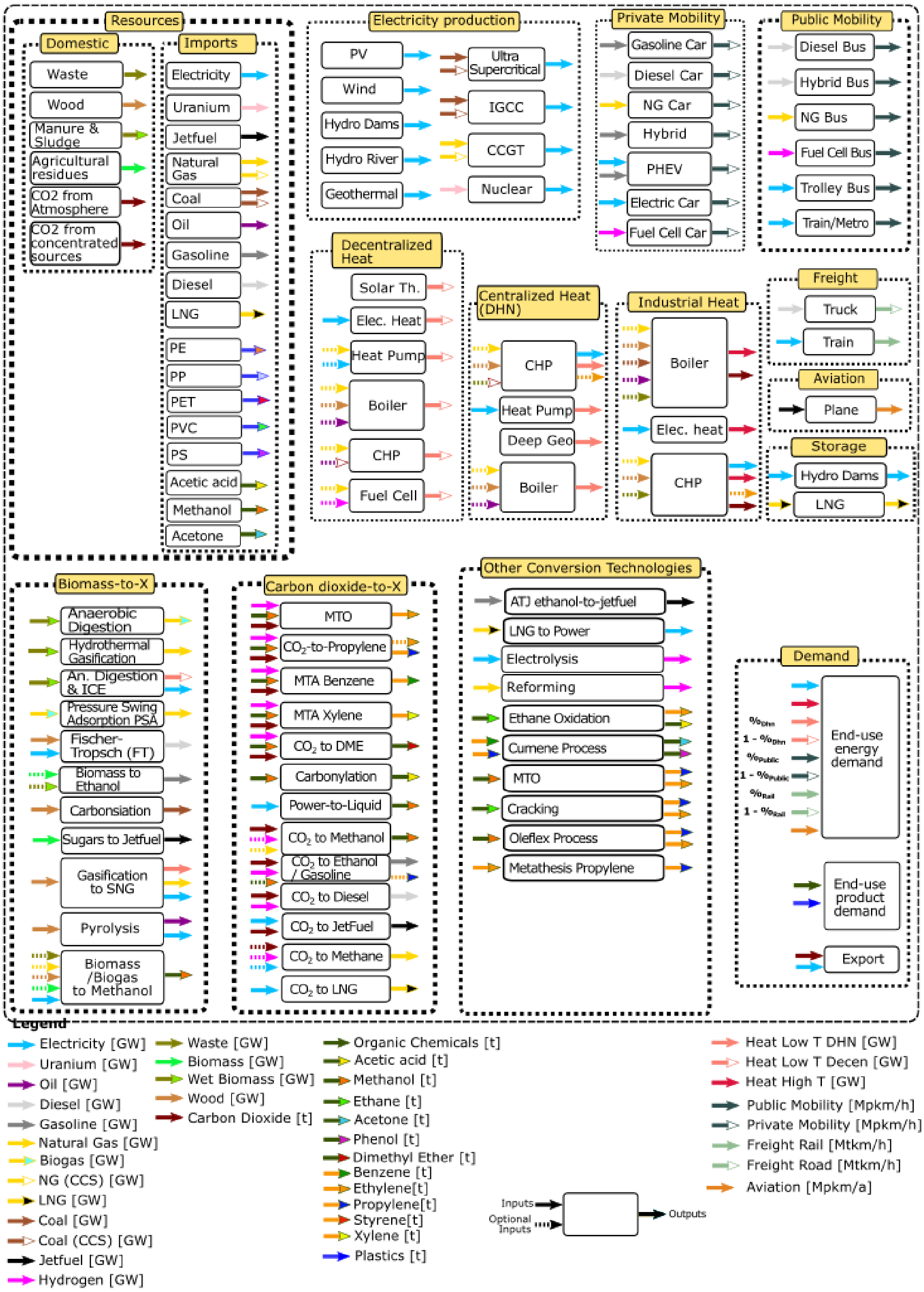

Figure 10. Application of the MILP modelling framework to the carbon system of Switzerland. Adapted from Moret (2017). Abbreviations: natural gas (NG), liquified natural gas (LNG), carbon capture and storage (CCS), liquified natural gas (LNG), synthetic natural gas (SNG), combined cycle gas turbine (CCGT), photovoltaic (PV), temperature (T), plug-in hybrid electric vehicle (PHEV), cogeneration of heat and power (CHP).

5.3 Sankey Diagrams

To make the model results easier to grasp, the output results are depicted using Sankey diagrams. For each scenario, Sankey diagrams are created both for energy flows as well as carbon flows. In all these diagrams, the sources come on the left side into the system. For the energy Sankey the sources are imported energy carriers like gasoline and natural gas, or power plants. On the right part the demands in mobility, transport, heat and electricity are shown. These are the boundary conditions given by the user. The part in between the sources and the demand is the framework given by the developed model and in each case it represents the solution of the optimization.

The carbon Sankey works similarly; the carbon sources are shown on the left (as the carbon part of energy carriers), and the carbon products (including carbon dioxide emissions) are on the right side. In the middle, the model converts the carbon sources into the end demand. With a colour set for each kind of carbon source used, its pathway through the Swiss system can be tracked.

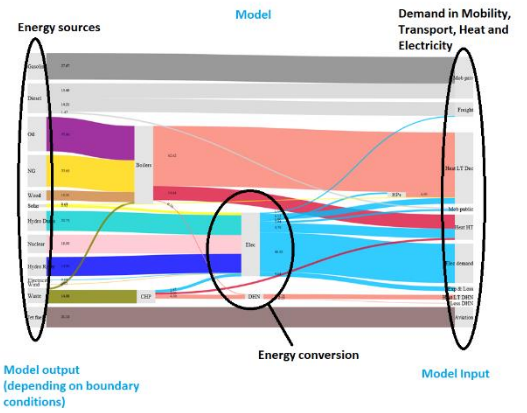

Figure 11. Example of a Sankey diagram of the energy flows in Switzerland. The energy flows are given in TWh/y.

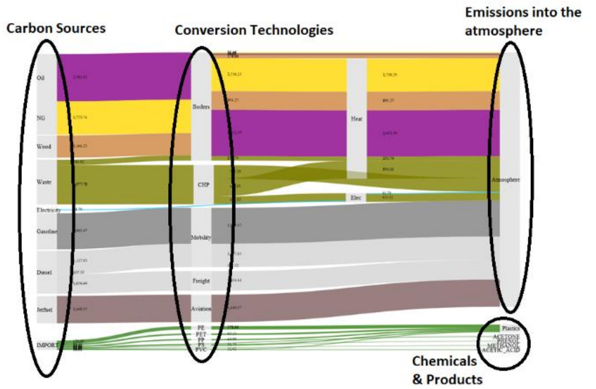

Figure 12. Example of a Sankey diagram of the carbon flows in Switzerland. The carbon flows are shown in kt/y.

The width of a carbon or energy stream in a Sankey diagram reflects the amount transported. However, though the streams can be compared with each other in the same Sankey diagram, their width cannot be compared between different Sankey diagrams. This is because depending on the scenario, the total energy or carbon content of a system changes.

5.4 Costs

Costs are typically a very difficult part in a model because of the diversity of the available data. In the expanded EnergyScope model developed in this project, the following costs are included:

- Material costs: import costs for imports; production costs for domestic sources (e.g. wood).
- Investment costs of the technologies: Total investment costs of a plant annualized with respect to the expected lifespan.
- Maintenance costs of the technologies: These include the costs for maintenance per year, excluding fuel costs.

The model includes therefore the total costs of the conversion technologies and of the sources. However, costs for infrastructure and end distribution are not included.

Examples of included costs:

- Costs of power plants.
- Costs of imported fuels and products.
- Costs of domestic sources (production costs), e.g. wood.
- Investment costs for the energy and carbon conversion technologies.
- Maintenance costs for the energy and carbon conversion technologies.

Examples of not-included costs:

- Costs for electrical and gas grid.
- Costs for cars, trucks and heat distribution systems.
- Transition costs: demolition of current installations and infrastructure, and the installation of a new or enlarged infrastructure.

6 Scenarios

Prognos AG have created three scenarios for their study „Die Energieperspektiven für die Schweiz bis 2050“: „business as usual“, „new energy policy“ and „political measures“ (Prognos AG, 2012). Scenarios like these will be implemented into the model.

Next to the already existing scenarios, the efficiency of various political measures are tested by taking the current situation (which can be verified) and only adjust some data according to the measure that is to be evaluated. An examples for political measures is the inclusion of stricter carbon tax or a ban on fossil based products like fuels / plastics.

As the developed model works as framework, different scenarios can be analyzed with it, like political measures or a change in consumer behaviour. The variation of possible scenarios is very large. Therefore this section presents a few indicative scenarios to showcase the possibilities of the methodology to design a new energy system and monitor the corresponding carbon flows.

Table 19. Description of the selected scenarios.

	SCENARIO NAME	DESCRIPTION
1	Today	Energy and carbon flows in Switzerland today.
2	Nuclear phase-out	Restrictions / Assumptions: • No nuclear power plants • Demand remains the same
3	Electric cars	Restrictions / Assumptions: • The type of cars used can be chosen freely by the model. • The restrictions for renewable electricity sources are loosened, so that the production doesn't limit the outcome. • The demand in mobility (in pkm) remains the same.
4	Cheapest heating system	Restrictions / Assumptions: • The model chooses freely the source that corresponds to the cheapest solution in order to meet the heat demand.
5	Ban on fossil fuels and nuclear phase-out	Restrictions / Assumptions: • Ban on all fossil fuels including jet fuel • No nuclear power • No deep geothermal
6	CO_2 taxes on fossil fuels	Step-by-step approach to find the prices for fossil energy carriers that would lead to a switch to renewable pathways.
7	New Energy Policy	The Swiss Federal Office of Energy has developed several scenarios for the future development of the energy system in Switzerland. One scenario is called "New energy policy" and bases mainly on improvement of technologies. Its main goal is the reduction of the CO2 emissions to 1-1.5 t per capita and year until 2050.

While analyzing the scenarios, the maximum yield that can be reached in Switzerland are set as boundary conditions (if not stated otherwise):

- Solar: 67 TWh (incl. roofs and facades of buildings) (BFE, 2019). This corresponds to the figures by Swisssolar (Meteotest, 2017), which defines a potential of 50 TWh PV and 10 TWh of thermal solar energy in Switzerland.
- Wind: 4.3 TWh (Energy Strategy 2050). (Prognos AG, 2012)
- Hydro Power: 38.6 TWh (Energy Strategy 2050). (Prognos AG, 2012)
- Wood: 14.08 TWh (BAFU, BFE, SECO, 2017)

The results of each scenario are listed in a table, which consists of three parts – costs, energy flow and carbon dioxide emissions. These figures are used for the comparison and the discussion of the scenarios.

	System costs	Here the total system cost are defined, which is the sum of the costs described in chapter 5.4.
	Total energy flow - electrical energy - other energy forms	The **total energy flow** shows the sum of all input energy carriers (domestic and imports). **Electrical energy** is the sum of the electricity produced in the system. This includes also the electrical power that is used for further conversion processes. The difference between the total energy flows and the electrical energy belongs to **other energy forms**. This includes especially heat production and mobility that is not covered by electricity. In the **brackets** behind the electrical energy and other energy forms, the percentage of domestic energy sources used for this energy form is declared. In power production, electricity from hydro and wind power plants, PV and nuclear power plants are regarded as domestic, only the imports are not domestic. In the other energy flows, sources like wood, waste and biomass domestic while all fossil fuels are imports.
	Carbon dioxide emissions	The CO_2 emissions of the system are divided in emissions from fossil energy sources and emissions from non-fossil energy sources. This division is chosen for the reader to understand, which emissions are problematic in regards of climate change, and which ones belong to a carbon cycle and will be captured by plants again.

6.1 Scenario 1 - Today

First, as reference, for validation and for comparison, the current carbon and energy flows are modelled.

Table 20. Swiss energy demand in 2017 (GWh/y) (BFE Prognos, 2018).

	Households	*Services*	*Industry*	*Transportation*	*Sum*
Low Temperature Heat – Space Heating	44'140	18'000	4'310	0	66'440
Low Temperature Heat - Hot Water	8'920	3'080	720	0	12'720
High Temperature Heat - Process Heat	1'530	580	24'360	0	26'470
Mobility	0	0	0	65'500	65'500
Electricity (Lighting, HVACR, I&C / Entertainment, Processes, others)	10'780	15'620	14'520	0	40'920
Total domestic energy demand	65'390	37'280	43'890	65'500	212'060
	(30.8%)	(17.6%)	(20.7%)	(30.9%)	(100%)

6.1.1 Heat from renewable sources

According to BFE (2018), in 2017 a total of 57 PJ/y (= 15'830 GWh/y) of heat was produced by renewables. The amount corresponds to 2.5 PJ/y (= 690 GWh/y) by solar panels, 16.7 PJ/y (= 4'640 GWh/y) by heat pumps, 28.7 PJ/y (= 7'970 GWh/y) by combustion of wood, 8.7 PJ/y (= 2'420 GWh/y) by combustion of waste and 1.0 PJ/y (= 280 GWh/y) by combustion of gas from sewage treatment plants. Renewable heat sources have a share of around 15% in the total heat production.

6.1.2 Electricity

In 2018, hydro parks in Switzerland had installed a total power capacity of 15'294 MW. This is comprised of 4'053 MW production from run-of-river (17'550 GWh/y), 8'152 MW from storage (17'221 GWh/y), 2'562 MW from pumped storage (1'557 GWh/y) and 527 MW from basic water flow plants (SFOE, 2018).

Table 21. Current status on the coverage of electrical power needs in Switzerland (GWh) (BFE, 2018).

	Power Production	*Percentage*
River Hydro Power Plant	36'700	25.9
Dam Hydro Power Plant		33.7
Nuclear Power Plants	19'500	31.7
CHP (fossil-based)	1'600	2.7
CHP (renewable)	1'200	2.0
Other Renewable Energies	2'500	4.0
Total	**61'500**	**100**

6.1.3 Mobility

In 2016, private mobility amounted to 132'200 Mpkm/y, from which 71% was covered by cars, 16% by trains, 2% by public buses, 2% by private buses, 0.4% by trolleys and 1% by trams. The total public transportation covers around 21% of private mobility (BFS, 2019). From the total public transportation of around 26'120 Mpkm/y, 83.8% are covered by trains, 10.2% busses, 5.1% by trams and 2.0% by trolley busses.

In 2017, the Swiss energy consumption in traffic was 308'000 TJ in total, including aviation and tank tourism, which is equivalent to 85'600 GWh/y. According to (BFS, 2019), this demand is covered by 32% by gasoline (27'400 GWh/y), 37% by diesel (31700 GWh/y), 25% by jetfuel (21'400 GWh/y), 4% by electricity (3'400 GWh/y) and 2% by gas and other energy carriers (700 GWh/y). Excluding tank tourism and international aviation, a total energy demand of 235'800 TJ/y (equivalent to 65'500 GWh/y) occurred in 2017:

Table 22. Total energy demand in Swiss traffic (GWh/y), excluding tank tourism and international aviation (BFS, 2019).

Sector	*Energy Demand*	*Percentage*
Road – Private Mobility	45'850	70
Road - Transport	10'480	16
Trains	3'280	5
Ships	460	0.7
Aviation (domestic)	980	1.5
Other/non-road	3'930	6
Total	**65'500**	**100**

6.1.4 Model Validation Results

The results of the model are compared to literature data for its validation. For this, the current demand is put into the model as boundary conditions. Also the percentage of each technology is defined according to the current situation. In Table 23 the results from the model calculated demand in power plants and fuel / heat sources are compared to data given by the Swiss Federal Office of Energy (SFOE / BFE / OFEN).

Table 23. Model validation results.

		Values from Model (TWh/y)	*Values from Literature (TWh/y) (BFE, 2018)*	*% Deviation*
Electricity	Nuclear	19.50	19.50	0.00
	CHP	2.82	2.80	0.71
	PV	2.36	2.28	3.51
	Wind	0.22	0.22	0
	Hydro Dam	20.56	20.72	-0.77
	Hydro River	16.33	15.95	2.38
Fuels and heat sources	Gasoline	27.67	27.67	0
	Diesel	30.63	31.82	-3.74
	Jetfuel	21.10	21.10	0.00
	Electricity (Import)	1.00		
	Gas	33.03	33.03	0.00
	Oil	35.80	35.54	0.73
	Wood	13.73	13.73	0.00
	Heat from waste (DHN)	2.24		
	Heat from heat pump	4.99	4.64	7.54
	Solar (thermal)	0.69	0.69	0.00

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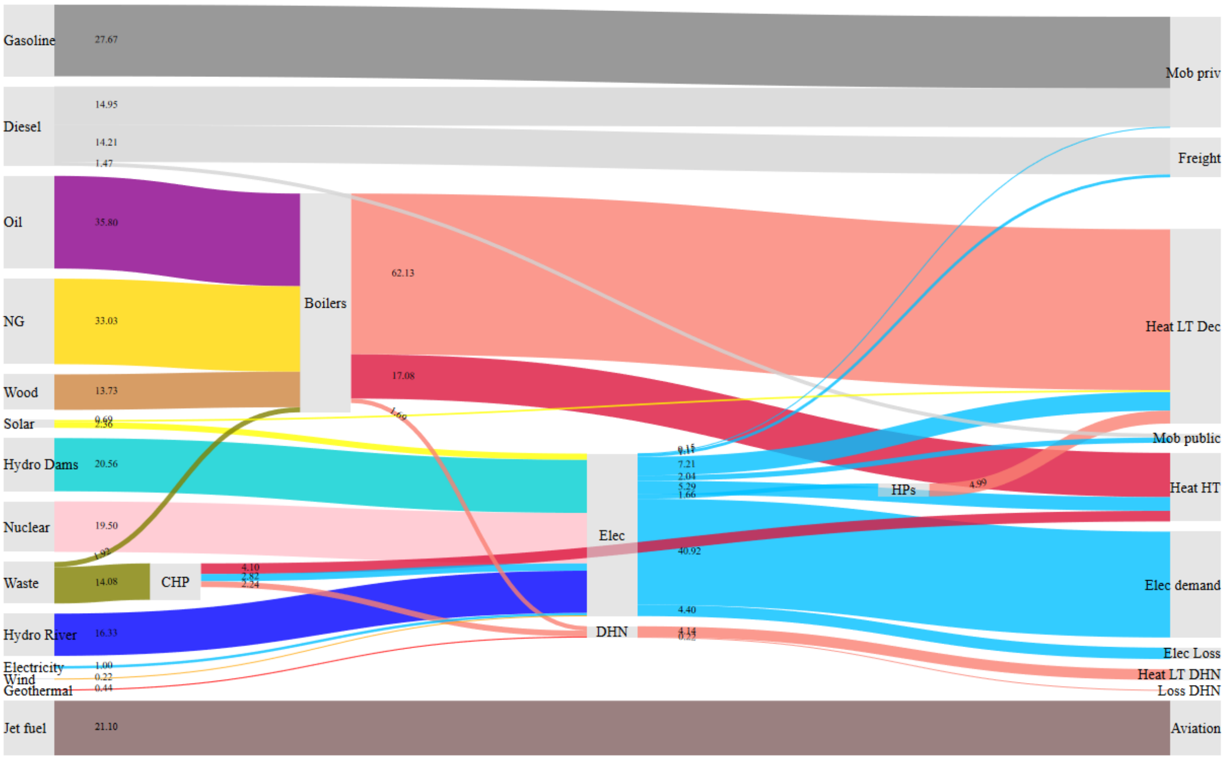

Figure 13. Energy flows in Switzerland in 2017 (TWh/y). The energy sources are on the left, and the demand is on the right. The streams in between represent the energy streams.

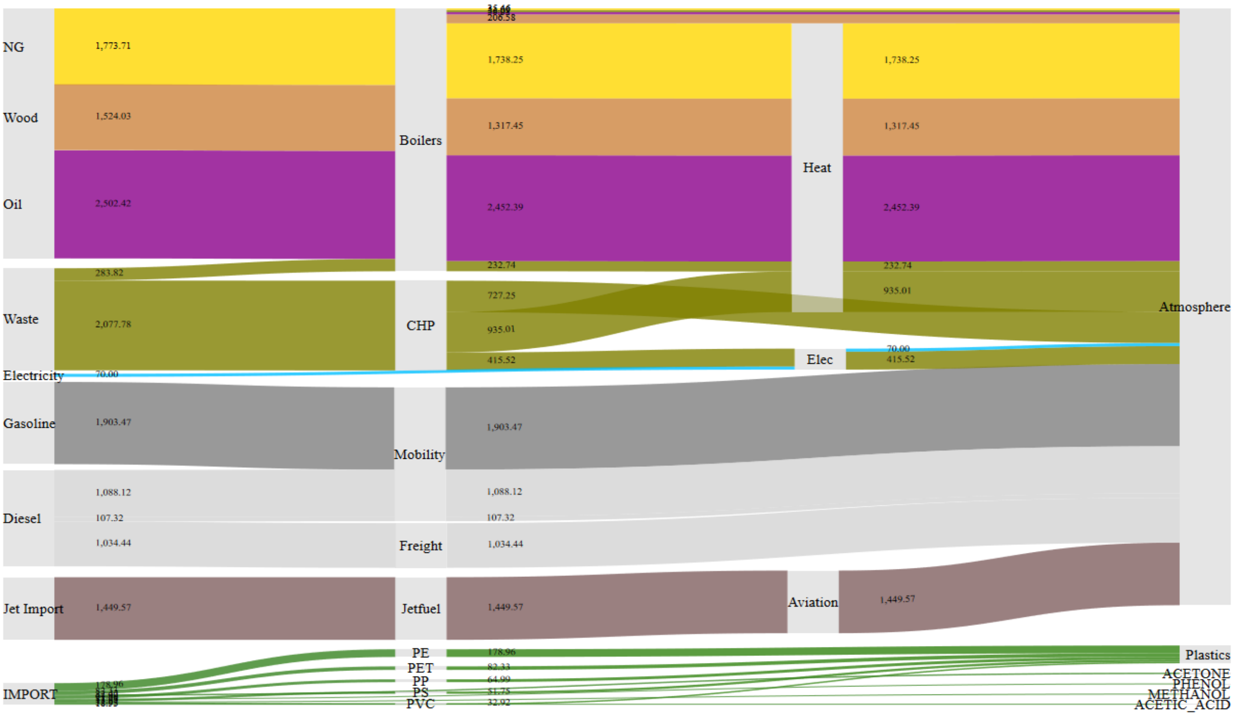

Figure 14. Carbon flows in Switzerland in 2017 (kt C/y). The carbon sources are on the left, and the demand is on the right. The streams in between represent the carbon streams.

Table 24. Today's system results.

	System costs	19.2 billion CHF/y
	Total energy flow - electrical energy - other energy forms	239.1 TWh/y 62.8 TWh/y (98.4 % domestic) 176.3 TWh/y (15.9 % domestic)
	Carbon dioxide emissions	40.7 Mt/y (fossil) 10.0 Mt/y (non-fossil)

The present situation is depicted in Figures 13 and 14 representing the energy and carbon Sankey diagrams respectively. The role of nuclear and hydro energy is evident to cover the electrical demands with only a small contribution of solar energy. Wood, oil and natural gas boilers are utilized to provide the heat needed for decentralized usage as well as cover the industrial heat demand. At present, the mobility needs are satisfied by imported diesel, gasoline and jet-fuels for ground and air transport respectively.

The flows of carbon dioxide shown in Figure 14 coincide with the energy flows and the majority ends up in the atmosphere as emissions. Only a small part corresponds to the import of polymers materials and industrial chemicals where the carbon is considered to be stored within the products.

It has to be noted that the carbon dioxide emissions shown here include both emissions from fossil and renewable energy sources. Thus, the total amount of emitted CO_2 is given.

According to Table 24, the total costs for the energy technologies amounts to 19.2 billion CHF/y and the total electrical output of the national system is 62.8 TWh/y. Finally, it can be seen that the CO2 emissions are dominated by the fossil part which represents 40.7 Mt/y out of the total 50.7 Mt/y emissions (around 80 %).

6.2 Scenario 2 - Nuclear phase-out

In this scenario, all nuclear power plants are shut down in order to evaluate the electricity production after a nuclear phase-out. The fossil streams (gasoline, diesel, oil, natural gas and jet fuels) remain the same as today, while the potential of other power plants is increased within their boundary conditions (only the non-fossil-based electricity sources were allowed to increase in this scenario). In order to make the scenario comparable to the situation of today, the demand in mobility, heat, electricity and aviation has been kept equal to the demand of the present. The energy flows are shown in the figure below

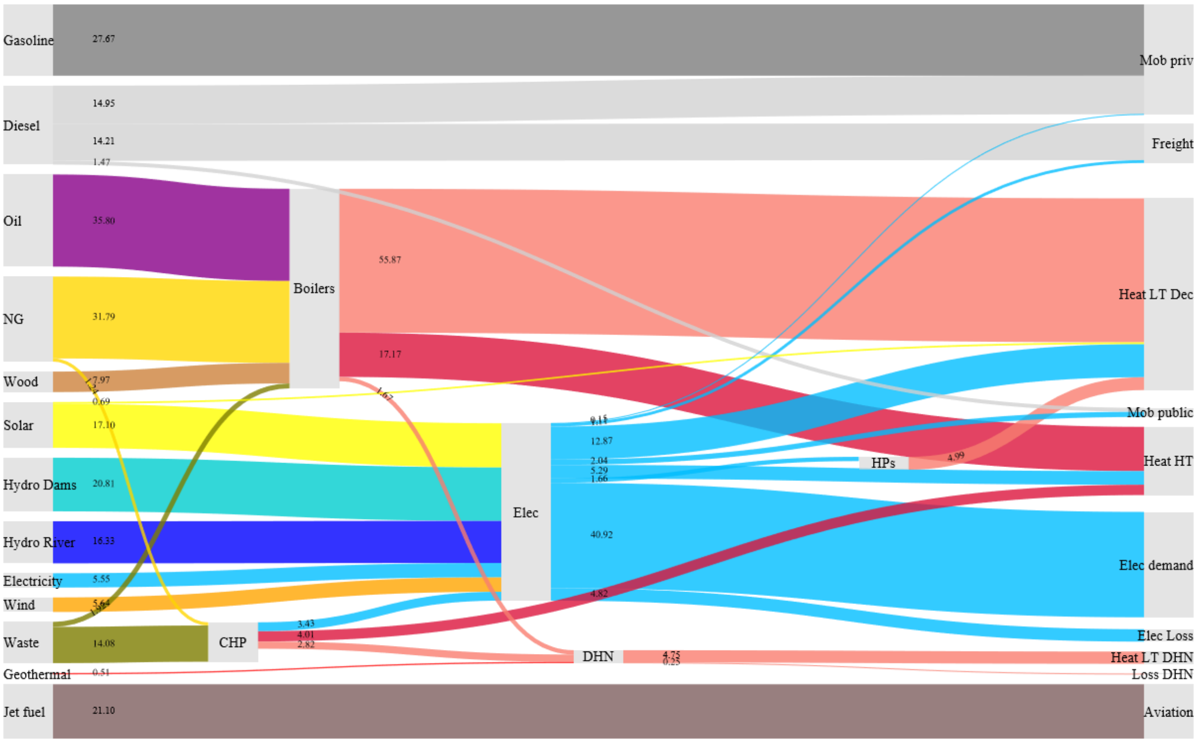

Figure 15. Energy flows in Switzerland for scenario #2 (Nuclear phase-out) (TWh/y).

As the nuclear phase-out only concerns the electricity part which the nuclear power plants satisfy today, the carbon flows Sankey diagram is of little importance as almost the same amount of carbon dioxide emissions (dictated by the same services demand) the emissions will again end up in the atmosphere. The nuclear power plants are considered emission-free.

What can be noted in the scenario is the important increase in the contribution of renewable sources such as wind, hydro and solar power which are at their maximum allowable values in order to compensate for the exclusion of nuclear from the power demand coverage. An equidistribution between the three renewable sources is noted. Finally, a small amount of natural gas is used in cogeneration plants this time.

Table 25 summarizes the total cost, electrical output and CO_2 emissions for the nuclear phase-out scenario.

Table 25. Scenario #2 (Nuclear phase-out) results.

	System costs	20.4 billion CHF/y
	Total energy flow - electrical energy - other energy forms	238.8 TWh/y 68.8 TWh/y (92.0 % domestic) 170.0 TWh/y (12.8 % domestic)
	Carbon dioxide emissions	41.9 Mt/y (fossil) 7.6 Mt/y (non-fossil)

From a first glance, one can see that the total electrical output and CO_2 emissions are very close to the ones calculated for the present situation scenario. The discrepancy noted can be attributed to the inclusion of natural gas in cogeneration plants which in turn increases the electrity produced but also the emissions. The most notable change, however, is the increase in the total cost, which is a direct consequence of the replacement of the nuclear plants with renewable power plants (wind, hydro and solar).

6.3 Scenario 3 - Electric cars

Today, the use of gasoline and diesel cars is common in Switzerland. Scenario 3 looks at the cheapest way of covering the demand in private mobility. The already installed infrastructure is not taken into account, i.e. the kinds of cars used can be chosen freely by the model. The restrictions for renewable electricity sources are loosened, so that the production doesn't limit the outcome. The demand in mobility (in pkm/y) is taken the same as today.

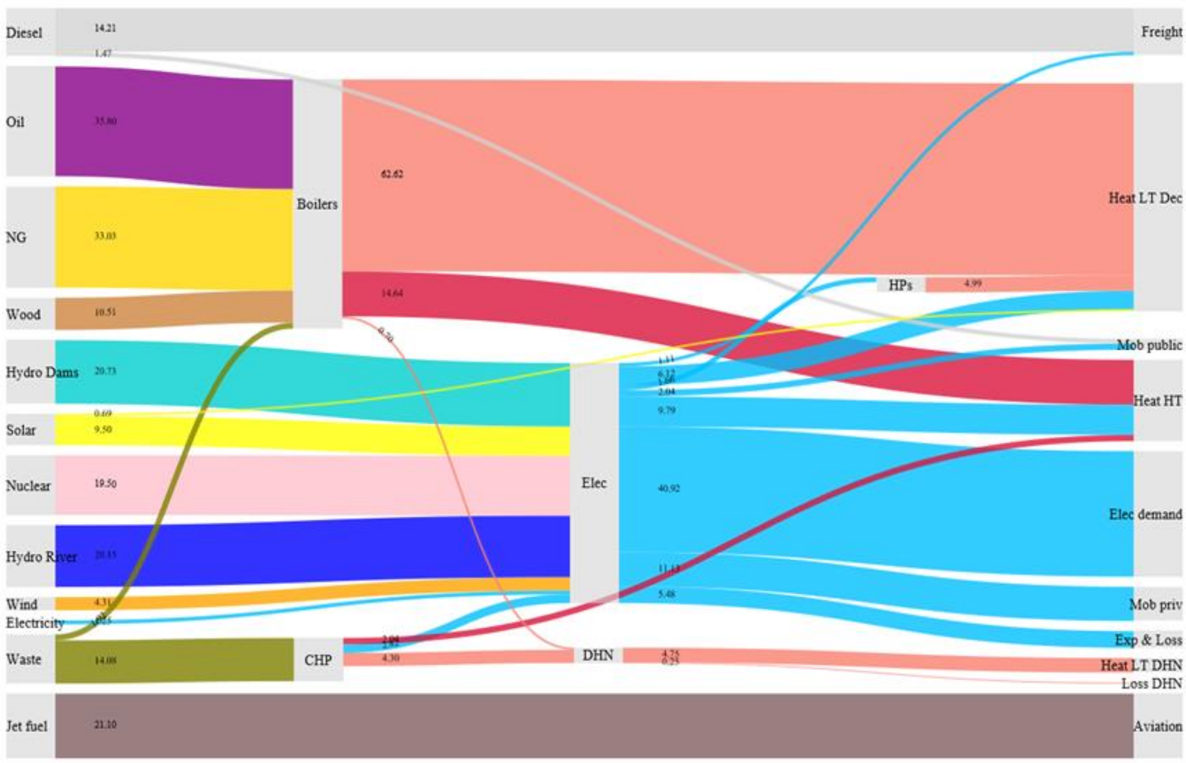

Figure 16. Energy flows in Switzerland for scenario #3 (Electric cars) (TWh/y).

By optimizing the total system costs, the model replaces all cars with electrical vehicles to cover today's private mobility demand. Again, wind and hydro power are running at their maximum, and there is a large increase in solar power. In this scenario, the nuclear phase-out hasn't been carried out yet.

With the electrification of the private mobility, the carbon flows will change, as no gasoline and less diesel is used for private mobility. Diesel is still used for freight transport, however.

The fossil carbon dioxide emissions of around 30 Mt/y come from aviation, freight transport, heating, burning of waste (counts 50% as fossil) and electricity import (based on the current CO_2 emissions in the European electricity production).

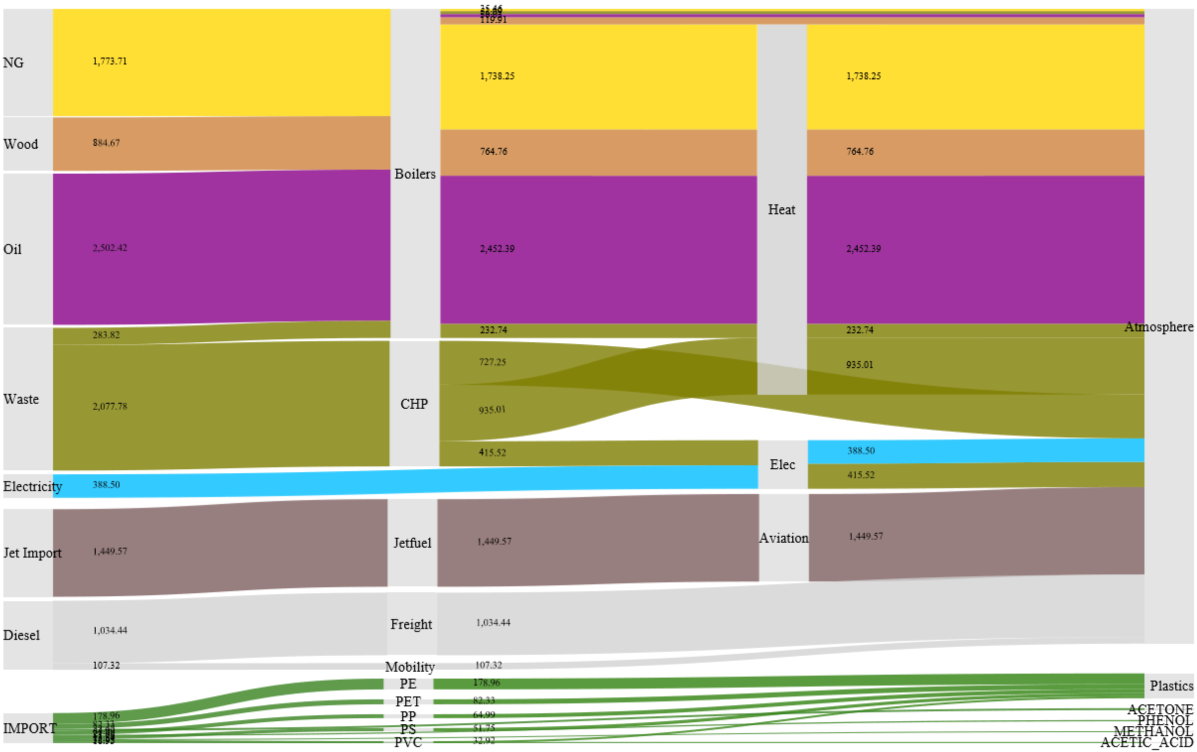

Figure 17. Carbon flows in Switzerland for scenario #3 (Electric cars) (kt C/y).

The carbon Sankey diagram is pretty straightforward, as the carbon flows are going straight from source (mostly fossil) to the conversion technologies and, in form of carbon dioxide, into the atmosphere. The electricity that appears in this chart is the amount that is currently imported and therefore contains the carbon dioxide that is emitted in its production. As all the emissions from private cars don't appear anymore, the total fossil carbon dioxide emissions are reduced by 25%. The latter is shown in Table 26 below:

Table 26. Scenario #3 (Electric cars) results.

	System costs	15.9 billion CHF/y
	Total energy flow - electrical energy - other energy forms	209.8 TWh/y 80.0 TWh/y (96.5 % domestic) 129.8 TWh/y (18.6 % domestic)
	Carbon dioxide emissions	31.2 Mt/y (fossil) 7.3 Mt/y (non-fossil)

Notably, the increase in the electrical output coincides with the demand for the electrification of the car fleet. Also, a decrease in the total cost is observed due to the reduction of imports.

6.4 Scenario 4 - Cheapest heating system

Similar to the previous scenario, in this scenario the model is allowed to choose the cheapest pathway for covering the heating demand in Switzerland, with unlimited possibilities of import. Again, the infrastructure is not taken into consideration, meaning that the choice between the heating options is not limited by any kind of techno-economic constraint.

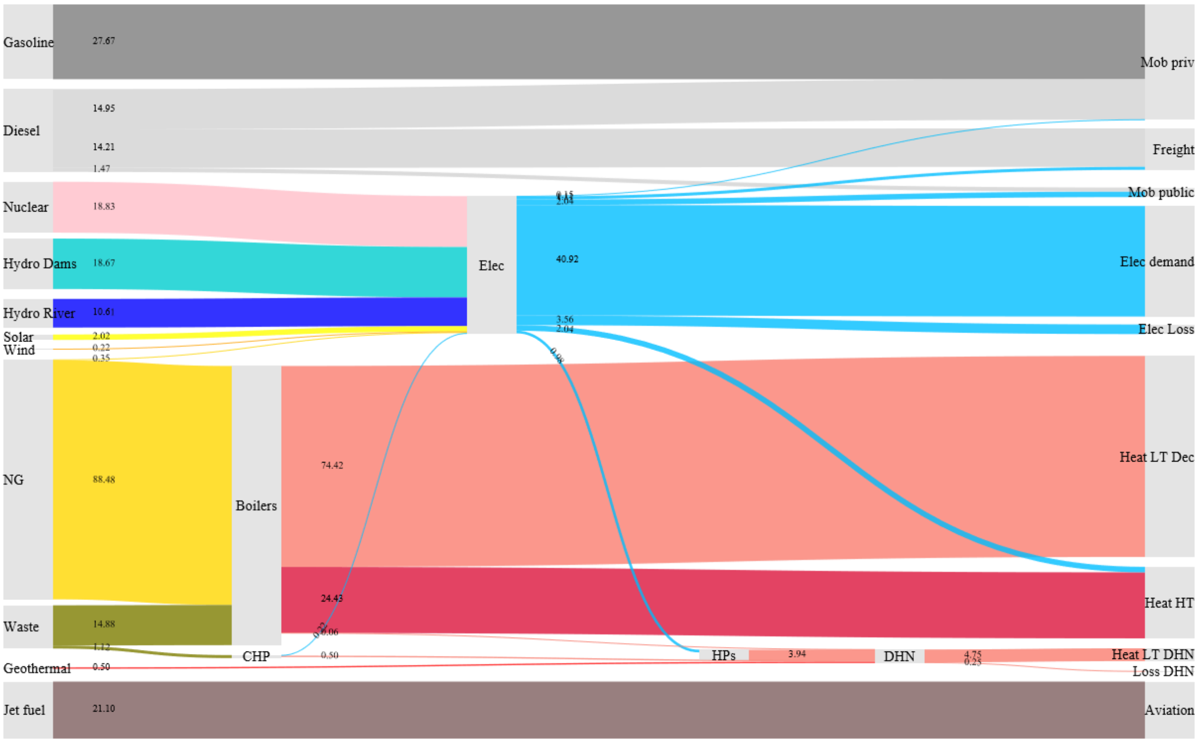

Figure 18. Energy flows in Switzerland, for scenario #4 (Cheapest heating system) (TWh/y).

As natural gas is rather cheap to import, it is almost the only source for covering the heating demand. Waste is also used in boilers to provide the necessary heat. Electricity is mainly produced by nuclear power plants and hydro dams, as these power plants are already installed (and were therefore left as boundary conditions in the model). A small part of the electricity demand is covered by natural gas in this scenario; therefore, the power production is decreasing.

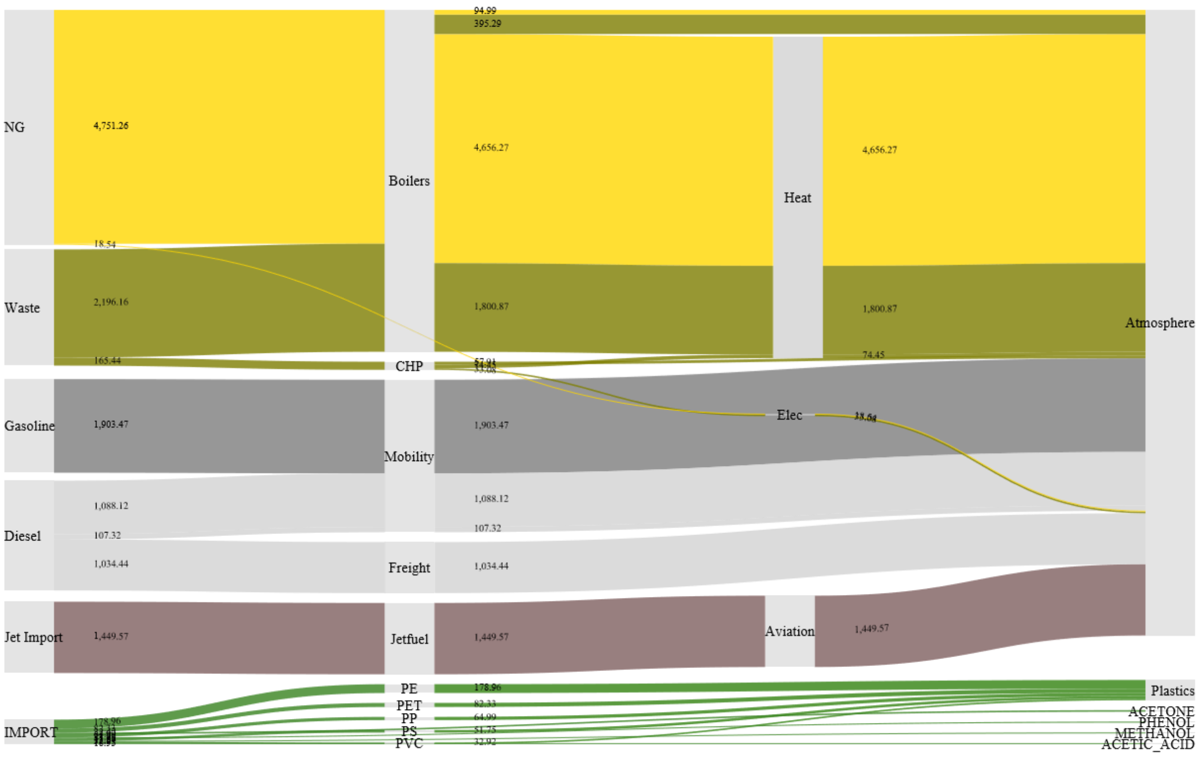

Figure 19. Carbon flows in Switzerland for scenario #4 (Cheapest heating system) (kt C/y).

Natural gas is predominant in this scenario, which is apparent in the carbon Sankey diagram (yellow stream at the top). The fossil carbon dioxide emissions are the same as in today's scenario. The decline in CO_2 emissions that would result from a replacement of oil heating with gas heating is compensated by an increased use of natural gas instead of electricity. The results of the scenario regarding total cost, electricity output and CO2 emissions are shown in Table 27 below:

Table 27. Scenario #4 (Cheapest heating system) results.

	System costs	16.5 billion CHF/y
	Total energy flow - electrical energy - other energy forms	235.3 TWh/y 50.9 TWh/y (100.0 % domestic) 184.4 TWh/y (8.9 % domestic)
	Carbon dioxide emissions	42.6 Mt/y (fossil) 4.0 Mt/y (non-fossil)

6.5 Scenario 5 - Ban on fossil fuels and nuclear phase-out

Enhancing the different scenarios to a completely renewable energy system, including a total ban on fossil fuels and nuclear power plants, but still importing fossil-based plastics, the energy system of Switzerland would look quite different to the one of today. This is depicted in Figure 20.

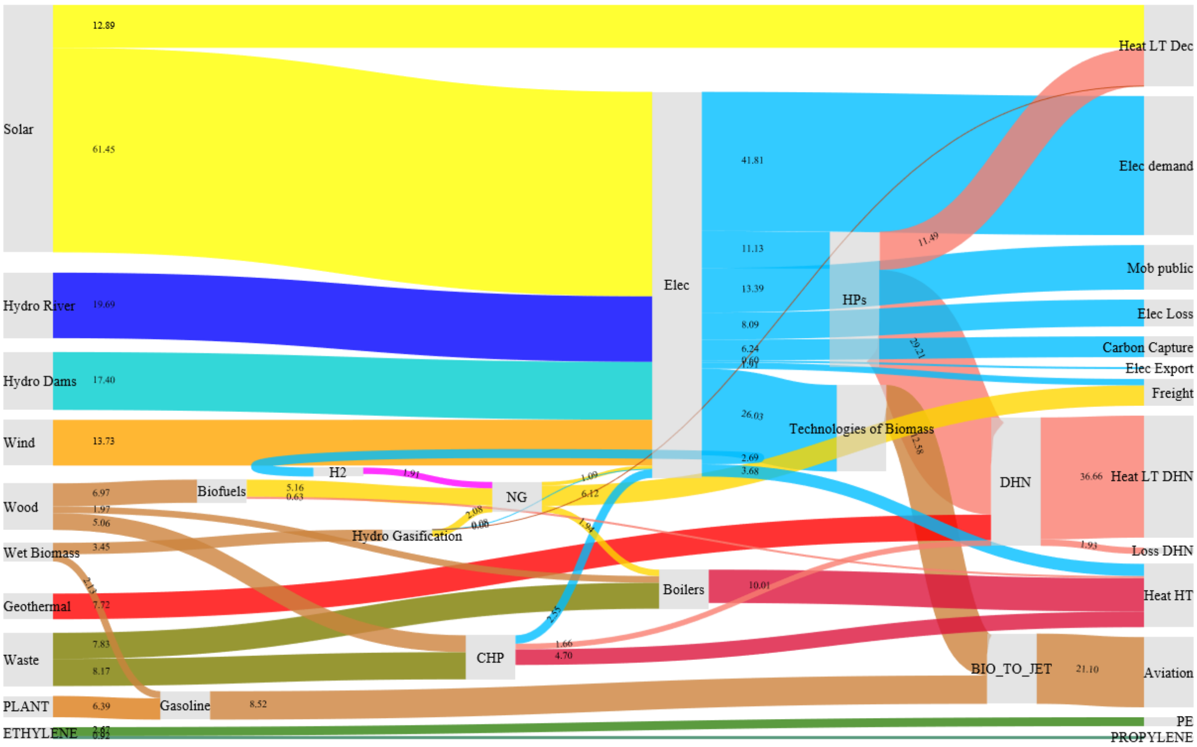

Figure 20. Energy flows in Switzerland for scenario #5 (Ban on fossil fuels and nuclear phase-out) (TWh/y).

The electricity production almost doubles compared to today, mainly covered by solar power. With over 60 TWh/y PV and 12 TWh/y thermal solar energy, the outcome exceeds the total potential of roofs and building facades that was defined by the Swiss Federal Office of Energy SFOE. The consequence is the additional use of other areas like an agricultural field as well. The total production of hydro power remains the same. Like for solar power, in this scenario the potential of wind power is exceeded as well. A possibility would be the installation of wind power plants abroad, in less dense populated and windier areas. Biomass and waste are used at their limits.

The energy Sankey diagram shows that the system becomes less linear compared to today. Nowadays, the energy sources are imported, then converted into electricity, heat or mobility, and then emitted into the atmosphere, or landfilled in case of the nuclear waste. However, the new system design has fluctuating power sources which then are used to first cover the electricity demand directly, but also to heat with heat pumps and for Power-to-X and Biomass-to-X technologies, which complement each other. It is seen that the electricity production is enhanced in this scenario. While part of the produced electricity is used to fuel electric cars and drive heat pumps for decentralized heat production, another part is used to convert captured carbon dioxide into synthetic fuels. These include synthetic natural gas using renewable H_2 from water electrolysis as well as synthetic jet fuels that supplement the bio-gasoline produced from plantations.

In the carbon Sankey diagram, the Power-to-X technologies as well as the biomass-to-X technologies can be tracked well. The biomass streams (brown) are used for the production of biofuels and heat. The carbon dioxide for the Power-to-X technologies is captured from the air (CO2_C).

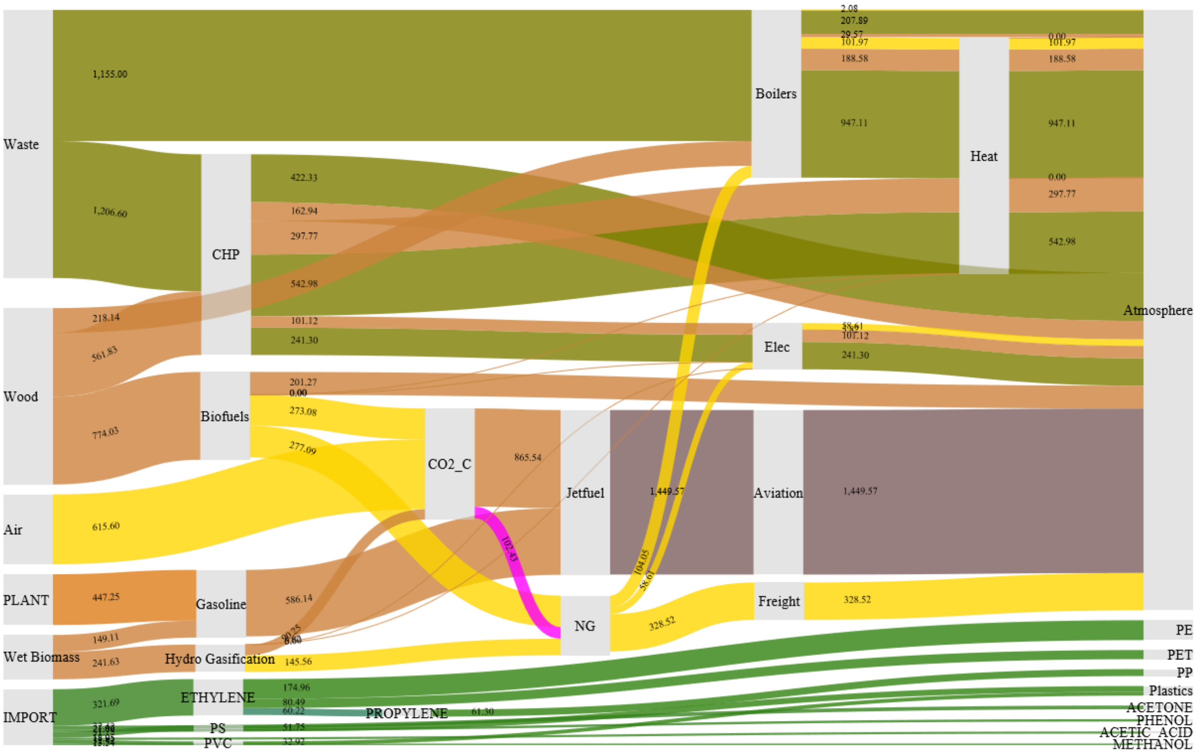

Figure 21. Carbon flows in Switzerland for scenario #5 (Ban on fossil fuels and nuclear phase-out) (kt C/y).

During the utilization of PV and wind power, which both have a lot of fluctuations in their production, the seasonality is also taken into account in the design. In the summer, when there is a surplus of electricity production surpassing the respective demand, the extra electricity is used for the heat in the industry as well as Power-to-X technologies. In the winter, biomass-to-X and industrial boilers are covering the demand. This effect can be seen in Figure 22 which presents the distribution of renewable power production as well as the usage of other energy conversion technologies during the course of one year, on a monthly time scale.

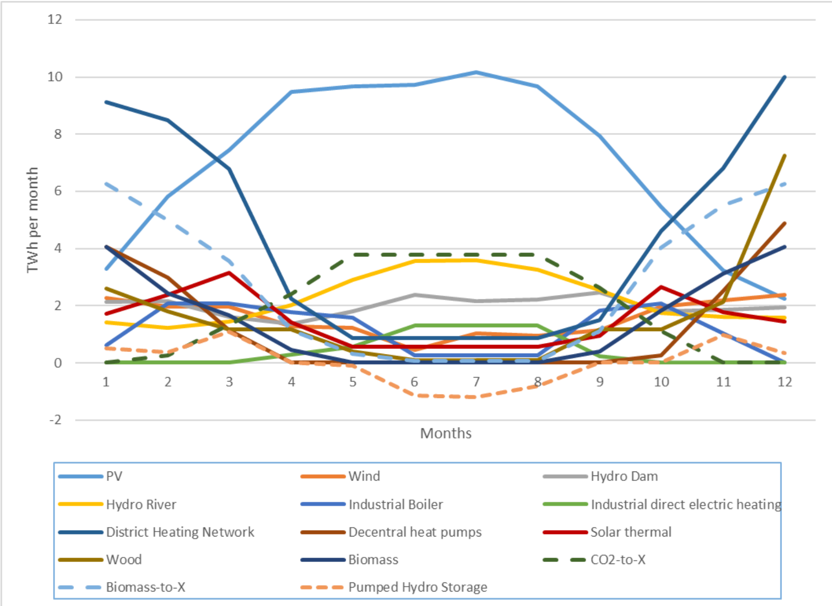

Figure 22. Seasonality in the usage of the different energy conversion technologies for scenario #5 (Ban on fossil fuels and nuclear phase-out)

Table 28. Scenario #5 (Ban on fossil fuels and nuclear phase-out) results.

	System costs	18.3 billion CHF/y
	Total energy flow - electrical energy - other energy forms	178.6 TWh/y 116.0 TWh/y (100.0 % domestic) 62.6 TWh/y (100.0 % domestic)
	Carbon dioxide emissions	3.6 Mt/y (fossil) 15.8 Mt/y (non-fossil)

Table 28 presents the overall results of scenario #5 where a big drop in the CO_2 emissions can be seen due to the banning of fossil resources and the subsequent use of renewable technologies. The remaining fossil carbon dioxide emissions come from the construction of the power plant, which is calculated with the current energy system. As mentioned above, the electricity production is drastically increased to accommodate the needs for electrical mobility and fuel synthesis. The total cost remains comparable to the current energy system, however, as in the previous scenarios the costs of new infrastructure development have not been taken into account.

6.6 Scenario 6 - CO_2 taxes on fossil fuels

When it comes to political measures that can be taken for reducing the fossil carbon dioxide emissions, the tool of CO_2 taxes is often mentioned. In this scenario, the minimum import prices of fossil fuels are evaluated that are needed for renewables to be economically competitive. The increase in the import price corresponds to the introduction of a CO_2 tax on the fuel.

With a step-by-step approach, the prices of fossil fuel are increased until the cost optimization leads to a renewable path. The starting price is the price that is currently paid at the Swiss borders, i.e. the import price.

Table 29. Fuel prices that constitute the penetration of renewables economically competitive.

Gasoline	370 CHF/tCO_2 (new price: 0.19 Fr./kWh, + 0.10 Fr./kWh)
Diesel	440 CHF/tCO_2 (new price: 0.20 Fr./kWh, + 0.12 Fr./kWh)
Oil	560 CHF/tCO_2 (new price: 0.19 Fr./kWh, + 0.15 Fr./kWh)
Kerosene	560 CHF/tCO_2 (new price: 0.20 Fr./kWh, + 0.14 Fr./kWh)
Natural Gas	750 CHF/tCO_2 (new price: 0.18 Fr./kWh, + 0.15 Fr./kWh)

With these prices, not the whole amount of the fossil fuels are replaced by renewably produced, but a large amount indeed. Diesel is replaced entirely, heating oil is reduced to 1.8 TWh/y per year (5% of today's amount). The imported amount of gasoline is still 9 TWh/y (one third of today) and around 14 TWh/y of natural gas is still fossil.

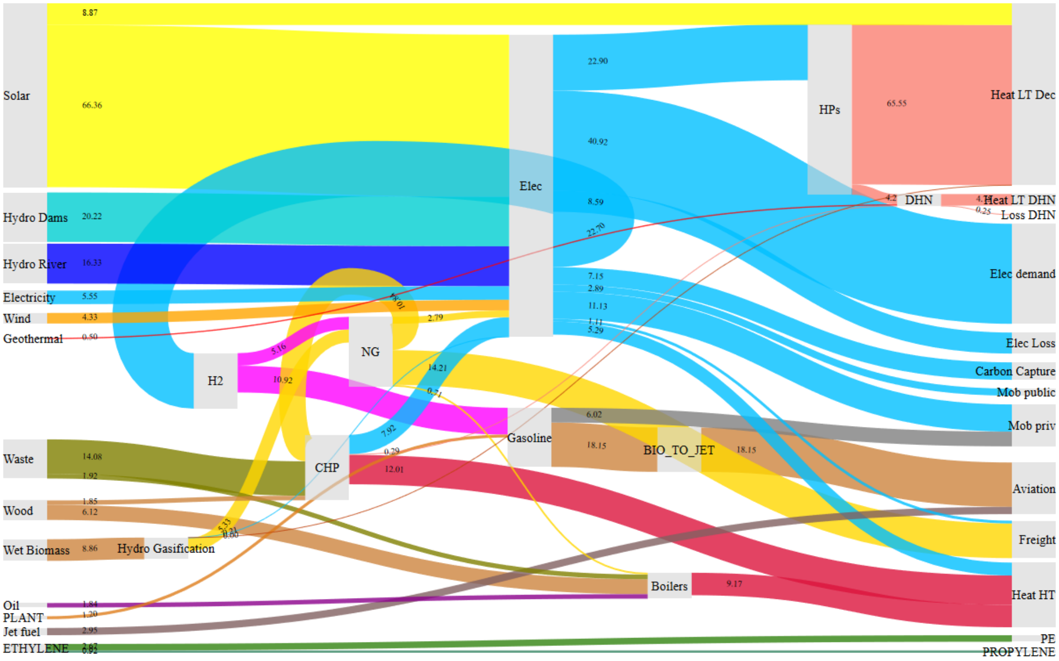

Figure 23. Energy flows in Switzerland for scenario #6 (CO_2 taxes on fossil fuels).

This scenario shows that some fossil fuels like gasoline don't need to be much more expensive for alternatives to be economically more competitive. The price of others, i.e. natural gas, has to be increased far more, also due to the fact that natural gas is currently imported at a very low price. It can be stated that an increase in the price of all fossil fuels to 0.19/0.20 Fr./kWh lead to a switch to renewables. Therefore, the increase in the price of each fuel is different for each fuel, but the end price of all of them is very close.

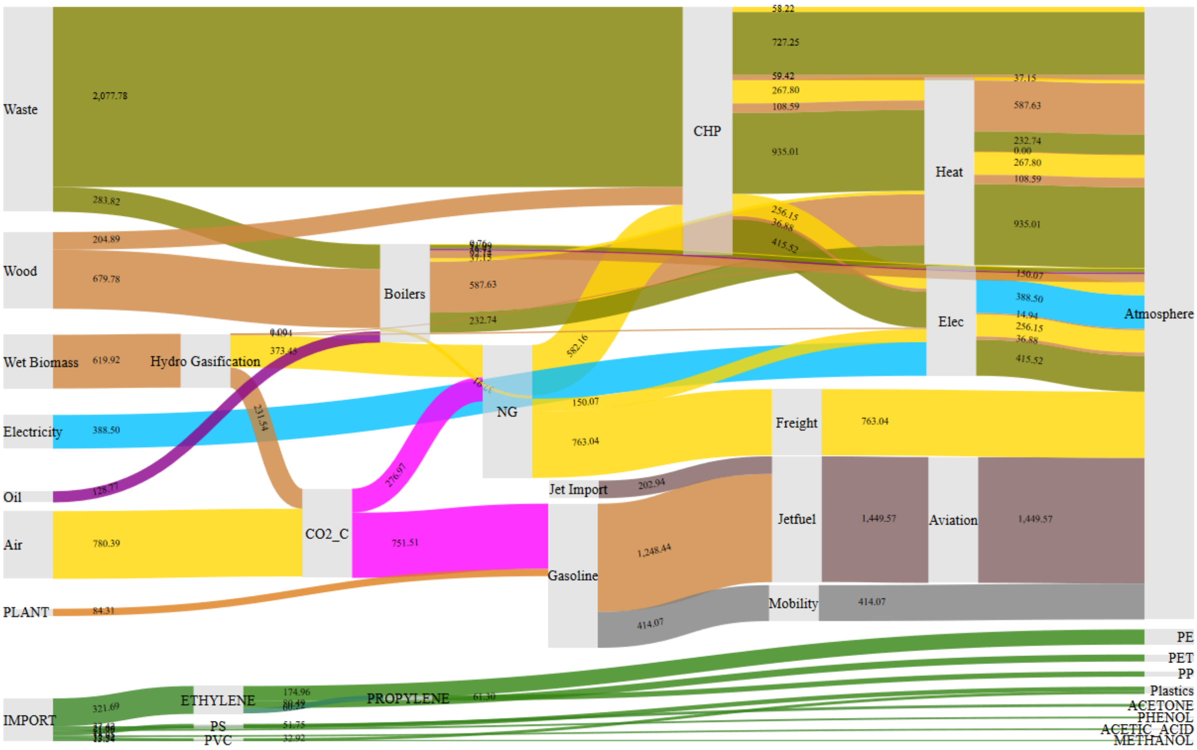

Figure 24. Carbon flows in Switzerland for scenario #6 (CO_2 taxes on fossil fuels).

Table 30. Scenario #6 (CO_2 taxes on fossil fuels) results.

	System costs	22.2 billion CHF/y (incl. taxes)
	Total energy flow - electrical energy - other energy forms	181.5 TWh/y 123.7 TWh/y (95.5 % domestic) 57.8 TWh/y (53.6 % domestic)
	Carbon dioxide emissions	12.9 Mt/y (fossil) 13.0 Mt/y (non-fossil)

In a fashion similar to scenario #5, Figure 25 depicts the seasonality in the usage of the technologies during scenario #6.

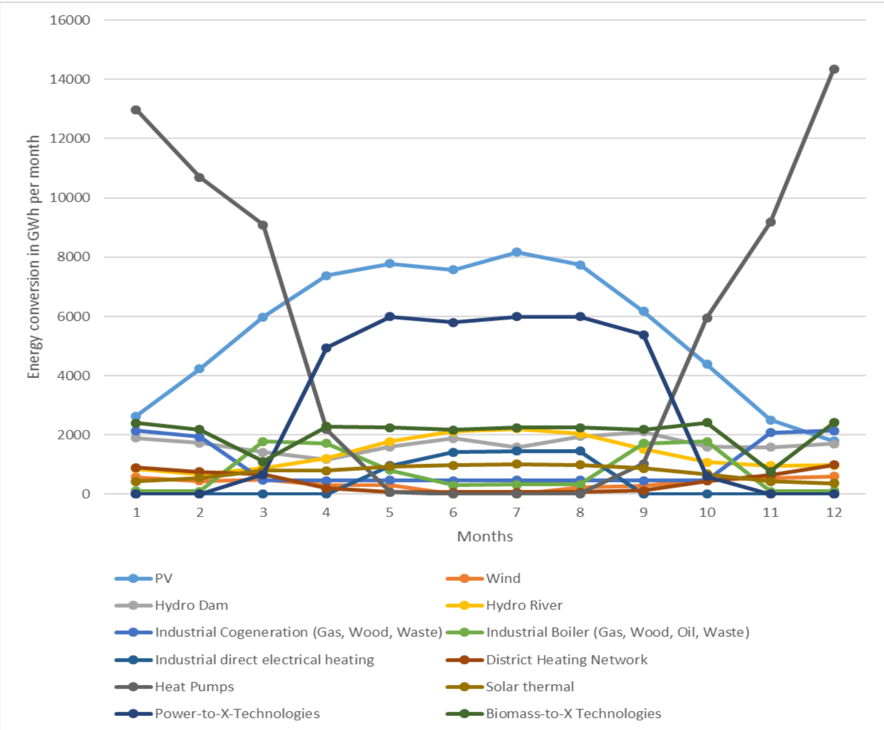

Figure 25. Seasonality in the usage of the different energy conversion technologies for scenario #6 (CO_2 taxes on fossil fuels).

6.7 Scenario 7 - New energy policy

The Swiss Federal Office of Energy has developed several scenarios for the future development of the energy system in Switzerland. One scenario is called "New energy policy" and bases mainly on improvement of technologies. Its main goal is the reduction of the CO_2 emissions to 1-1.5 t/y per capita until 2050. In (Prognos AG, 2012) the following boundary conditions are defined:

- Increase of the population to 9.0 millions
- Increase in private mobility to 137'000 Mpkm/y (2035) and 140'300 Mpkm/y (2050)
- Increase in freight transport to 39'300 Mtkm/y (2035) and 39'700 Mtkm/y (2050)
- Nuclear phase-out until 2034

The total energy demand declines in this scenario by 42% until 2050 (compared to 2000). This is summarized in Table 31 below:

Table 31. Total annual energy demand per sector for the years 2035 and 2050 according to the SFOE scenario "New energy policy" (Prognos AG, 2012).

	Households	*Services*	*Industry*	*Transportation*
Low Temperature Heat – Space Heating	*2035: 93.6 PJ* 2035: 26'000 GWh *2050: 50.1 PJ* 2050: 13'920 GWh	*2035: 54.3 PJ* 2035: 15'080 GWh *2050: 42.9 PJ* 2050: 11'920 GWh	*2035: 18.0 PJ* 2035: 5'000 GWh *2050: 15.3 PJ* 2050: 4'250 GWh	2035: 0.0 GWh 2050: 0.0 GWh
Low Temperature Heat - Hot Water	*2035: 28.3 PJ* 2035: 7'860 GWh *2050: 24.9 PJ* 2050: 6'920 GWh	*2035: 9.4 PJ* 2035: 2'610 GWh *2050: 8.6 PJ* 2050: 2'390 GWh	*2035: 4.7 PJ* 2035: 1'310 GWh *2050: 5.3 PJ* 2050: 1'470 GWh	2035: 0.0 GWh 2050: 0.0 GWh
High Temperature Heat - Process Heat	2035: 0.0 GWh 2050: 0.0 GWh	2035: 0.0 GWh 2050: 0.0 GWh	*2035: 62.7 PJ* 2035: 17'420 GWh *2050: 50.9 PJ* 2050: 14'140 GWh	2035: 0.0 GWh 2050: 0.0 GWh
Private Mobility	2035: 0.0 GWh 2050: 0.0 GWh	2035: 0.0 GWh 2050: 0.0 GWh	2035: 0.0 GWh 2050: 0.0 GWh	Private Mobility: 2035: 137'000 Mpkm 2050: 140'300 Mpkm Freight Transport: 2035: 39'300 Mtkm

				2050: 39'700 Mtkm
Electricity (Lighting, HVACR, I&C / Entertainment, Processes, others)	*2035: 40.6 PJ* 2035: 11'280 GWh *2050: 49.1 PJ* 2050: 13'640 GWh	*2035: 57.5 PJ* 2035: 15'970 GWh *2050: 56.8 PJ* 2050: 15'780 GWh	*2035: 39.5 PJ* 2035: 10'970 GWh *2050: 32.9 PJ* 2050: 9'140 GWh	2035: 0.0 GWh 2050: 0.0 GWh

According to the SFOE scenario, the following fossil energy carriers are used to cover that demand:

Table 32. Fossil energy sources used annually in Scenario #7 "New Energy Policy" (Prognos AG, 2012).

Energy carrier	*Demand in 2035*	*Demand in 2050*
Oil	12'780 GWh (46.0 PJ)	5'500 GWh (19.8 PJ)
Natural Gas	21'110 GWh (76.0 PJ)	14'140 GWh (50.9 PJ)
Gasoline	8'810 GWh (31.7 PJ)	3'560 GWh (12.8 PJ)
Diesel	11'080 GWh (39.9 PJ)	4'810 GWh (17.3 PJ)

For modeling this scenario, the above values are used as the upper limits in the availability of the fossil resources.

The above mentioned demand in 2035 as well as the given boundary conditions lead to a large increase in the electricity demand and therefore to an increase in the electricity production (especially as nuclear power plants have been phased-out until 2035). Low temperature heat demand is covered by heat pumps, while the high temperature demand is covered mainly by oil and partially by waste. Natural gas is used for the increased electricity demand, as well as photovoltaic and wind power plants (of which the output shows a large increase compared to today). As the use of natural gas is restricted by the aforementioned boundary conditions, it is complemented by converting biomass via hydrothermal gasification.

For the transport of freight the available diesel is used and the rest of the diesel produced renewably from hydrogen and carbon dioxide via fuel synthesis. The private mobility is based on electricity usage and for this reason the available gasoline is not used anymore but instead, the electrical output of the system is enhanced. The aviation demand is the same as today and is still fuelled by fossil jet fuel, as the energy strategy only covers domestic flights and doesn't include international travels.

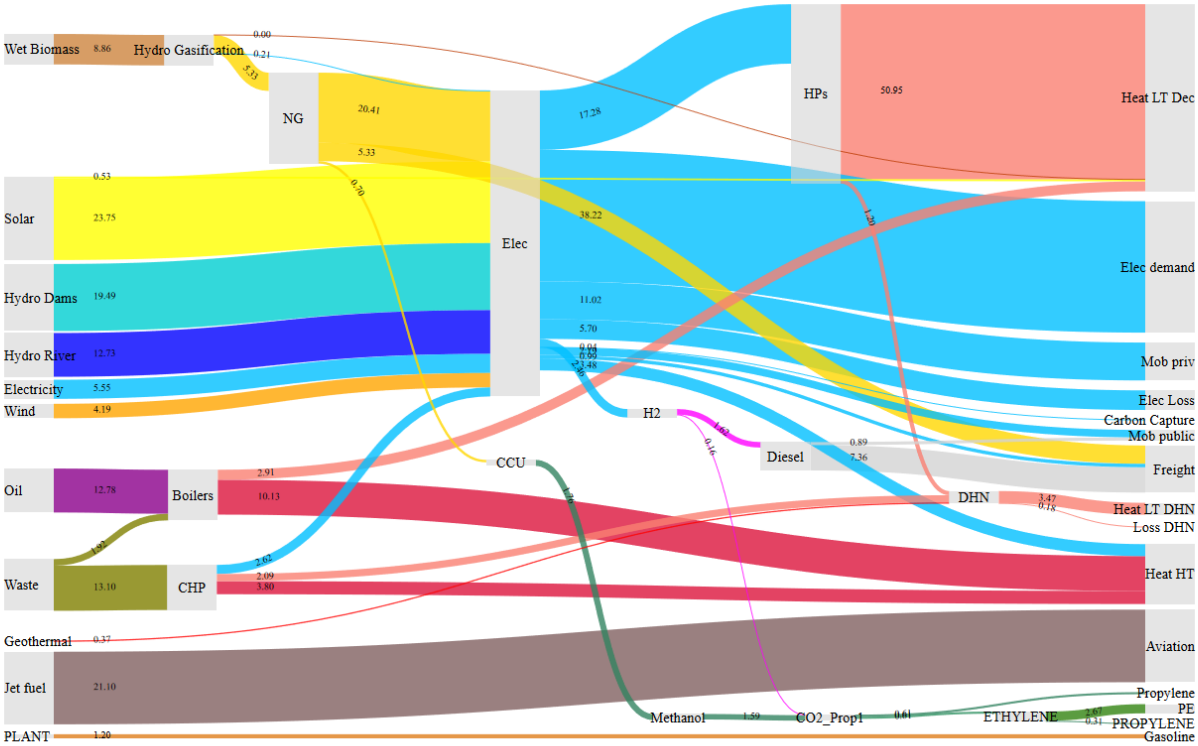

Figure 26. Energy flows in Switzerland for scenario #7 (New energy policy - 2035) (TWh/y).

The corresponding carbon Sankey diagram is seen in Figure 27 below.

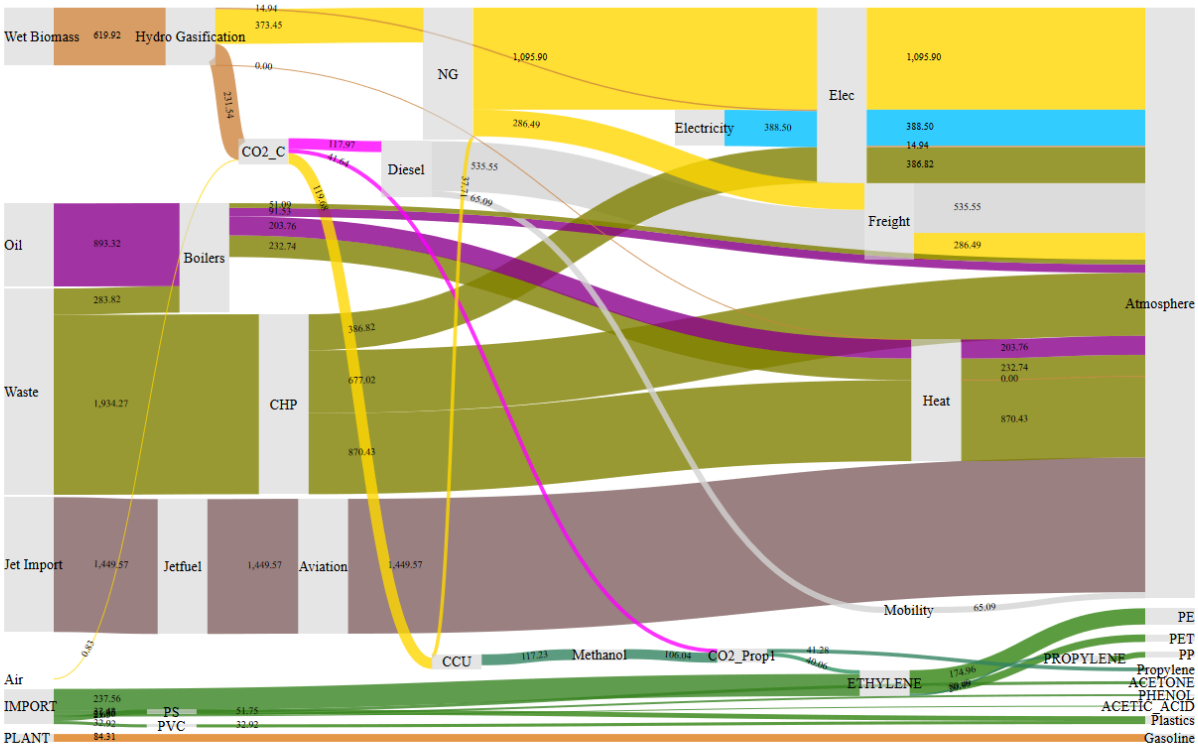

Figure 27. Carbon flows in Switzerland for scenario #7 (New energy policy - 2035) (kt C/y).

In the carbon Sankey diagram the combination of biomass and Power-to-X technologies is shown by the stream at the top. There, the gasification of wet biomass produces carbon dioxide which is then used to produce (in combination with hydrogen) diesel for freight transport. Captured carbon dioxide from processes or air is also used for chemicals synthesis, which in turn lead to the production of bio-materials (bio-polymers).

Table 33. Scenario #7 (New energy policy) results.

	System costs	13.2 billion CHF/y
	Total energy flow - electrical energy - other energy forms	153.3 TWh/y 89.0 TWh/y (70.8 % domestic) 64.3 TWh/y (37.0 % domestic)
	Carbon dioxide emissions	16.9 Mt/y (fossil) 6.3 Mt/y (non-fossil)

7 Discussion of results

In the following table, the results from the selected scenarios are collectively presented.

Table 34. Comparison of scenario results.

	SCENARIO	TOTAL ENERGY DEMAND (TWH/Y)	ELECTRICITY DEMAND (TWH/Y) (% DOMESTIC)	DEMAND IN OTHER ENERGY FORMS (TWH/Y) (% DOMESTIC)	CO_2 EMISSIONS FROM FOSSIL SOURCES (MT/Y)	SYSTEM COSTS (BCHF/Y)
1	Today	239.1	62.8 (98.4%)	176.3 (15.9%)	40.7	19.2
2	Nuclear phase-out	238.8	68.8 (92.0%)	170.0 (12.8%)	41.9	20.4
3	Electric cars	209.8	80.0 (96.5%)	129.8 (18.6%)	31.2	15.9
4	Cheapest heating system	235.3	50.9 (100%)	184.4 (8.9%)	42.6	16.5
5	Ban on fossil jet fuels	178.6	116.0 (100%)	62.6 (100%)	3.6	18.3
6	CO_2 taxes on fossil fuels	181.5	123.7 (95.5%)	57.8 (53.6%)	12.9	22.2
7	New energy policy	153.3	89.0 (70.8%)	64.3 (37.0%)	16.9	13.2

It is seen from Table 34 that among the scenarios presented in the previous section, the current situation in Switzerland has the largest total energy demand compared to the other cases. This demand mainly refers to heating and mobility requirements, the majority of the resources for which is imported. During the phasing-out of the nuclear power plants, no significant changes in the resulting energy requirement and carbon flows is observed. This was to be expected however, as the target in this scenario is to satisfy the same demand, with a different set of technologies. The latter is the reason for the slightly larger energy system cost. A yearly increment of 6 TWh in electricity demand is observed which in turn results in more fossil based CO_2 emissions.

In the case of the usage of electric cars, the extra electricity needed (17.8 TWh/y) is provided mainly by solar energy. This helps reduce the fossil CO_2 emission by more than 23% compared to the current state scenario. Additionally, the employment of solar panels to provide the power for a portion of the mobility sector results in the reduction of the imports of fuels for the car fleet, as the private mobility is fully serviced by electrical cars in this case. This can be seen in Table 34 as a decreased demand of the other energy sources, aside from electricity.

Interestingly, if only an economic consideration of the objective in designing a scenario is followed, such as in the case of scenario #4 the result is an increased use of natural gas. In this case, as mentioned above, the option of importing natural gas and producing heat in boilers is the cheapest one compared to new technologies involving for example biomass conversion technologies. As the import of natural gas is not constrained by anything, it remains the prevalent choice. This of course has a direct impact in the CO_2 emissions as well as the energetic autonomy of the system as only 8.9 % of the necessary energy (excluding electricity) is produced based on Switzerland's own resources.

On the other hand, the energetic autonomy is inversely related to the imports; and in the case of scenario #5 where no fossil import is allowed, the designed system has to compensate for the energetic needs based on the existing resources. As seen in Table 34 this results to the entirety of the energy produced domestically (i.e. using own resources). The ban on fossil imports as well as their overall utilization is a direct consequence of the elimination of the largest part of the fossil CO_2 emissions (> 91%). The remaining reported fossil emissions are only attributed to the construction of the energy conversion plants and not to the operational emissions. Electricity plays a major role in this case as it is the intermediate state for producing most of the services needed. Technologies such as power-to-gas using captured CO_2 from power plants or the atmosphere, guide the usage of electricity for the production of gaseous and liquid synthetic biofuels. Furthermore, the ban on fossil imports, also including kerosene for aviation, leads to the increase of the synthetic jet-fuels production. Lastly, the total system cost for this case remains comparable to the current scenario. However, as mentioned earlier, the costs of the infrastructure change have not been accounted. This means that the reported costs refers only to the development, installation and operation of new technological pathways assuming that the no big changes have to be done to the country's infrastructure such as the modifications on the fuel distribution network and the availability of the area for solar panels and wind farms to name a few.

The taxation policy adopted in scenario #6 leads to an increase of the total system costs (15.6% compared to the current state scenario). However, it should be noted that while in this case the penetration of renewables in the energy mixed is imposed, this does not mean that the entirety of the energy demand is satisfied using renewables. A small degree of freedom in importing fossil resources (e.g. oil, jet-fuels) is allowed. The latter can be reflected in the increased fossil CO_2 emissions compared to scenario #5. The higher cost of the energy system in this scenario is principally linked to this fact as well. As nearly 60% of the natural gas resources necessary for the energy system are imported at a much higher price than today, determined by the constraint of maximizing renewables use such as solar but relaxed by allowing imports, the economic burden of this amount is increased. The taxation policy does influence the rest of the imported resources such as gasoline and kerosene but to a lesser extent as the new import price is close to the current one.

Finally, in the last examined scenario, a projection of the energy system into the future is made. From Table 34, it can easily be observed that the overall energy production has decreased by a lot (35.9% compared to the situation of today) based on the associated demand prediction given by the SFOE scenario. This reduced capacity in turn, has a direct impact on the system costs. It should be noted that in this case, the imposed defossilization dictates the use of alternative (and renewable) pathways of power production. Although the inclusion of imports is not forbidden, it is reduced according to the SFOE scenario and therefore technologies combining CCU and fuel synthesis are used to satisfy the remaining demand in fuels. Also noteworthy compared to the base case scenario is the increase in the usage of heat pumps for the provision of the necessary heat. Overall, the reduction of the energy demand (35.9%), the reduction of the fossil-based emissions by 58.5 % as well as the total cost by 31.25% compared to today's situation, together with the relative increase in country's energy autonomy resulting from the incorporation of renewable technologies in the energy mix.

It should be noted at this point that as mentioned in the previous sections, two important aspects have not been fully considered during the design of the new energy systems, namely the cost of infrastructure change for the case where new technologies are proposed, as well as the uncertainties associated to the data and the predictive power of the model itself. The scope of this project is to provide a guiding light towards the direction that the future energy system could take; thus, detailed system design was avoided at this point. The uncertainty in the availability of the resources is known by some data sources used in this project to be in the range of 5-10%, and further refinement of the initial data would further increase the accuracy in the results of the model. However, it should be pointed that obtaining accurate values for such a large system as a country is a strenuous task. On a second level, the simplified fashion in which the link between the resources and the services is implemented in the model serves only the fast acquisition of results, while detailed calculations on process design are avoided. This helps derive answers in a very short amount of time (seconds), but at the same time limits the accuracy of the final results due to the simplifications and assumptions during the implementation into the model. However, as this model is used as a tool to have a fast and reliable indication on the behaviour of the energy systems under varying conditions, the rigour and predictive capabilities of the model are deemed satisfactory for this purpose. To better accommodate the implications on the above, sensitivity studies have to be conducted in the future in order to examine the behaviour of the obtained solutions to the aforementioned uncertainty parameters.

8 Conclusions and outlook

Overall, the project "Carbon Flows in the Energy Transition" provides a large and comprehensive database of energy resources and demand for the case of Switzerland as well as a generic model for the determination of the optimal transition from the raw materials to the products, able not only to define the intermediate energy transformation steps, but also quantify the energy and carbon flows across the entire conversion paths. In this framework and given the appropriate set of input data, this tool can be used to model any energy system by considering an embedded set of relevant technologies. As shown in this study, the model can also be used to emulate possible scenarios, corresponding to different energy policies, simply by modifying the set of initial assumptions. The outcome in each case is an optimally designed energy system, with respect to an economic and/or environmental objective, supplemented by constraints that define the relations between the model and real-life restrictions and assumptions.

Based on the results from the scenarios that were presented in the previous sections it appears that the carbon-based resources are playing an important role in the defossilisation of the energy system of Switzerland, together with renewable resources such as solar and wind power. Fossil carbon emissions can indeed be reduced by using renewables and bio-based resources in the energy mix; however, the emissions arising from the construction of the conversion plants can not be completely evaded. Nonetheless, the introduction of biomass and renewable energy technologies has proven to provide drastic CO_2 emissions reduction, reaching up to 90%. Crucial to that is the utilization of the carbon itself as a resource for synthetic fuels and biomaterials production. It is seen by some of the scenarios presented in this project that by employing a combination of CCU and Power-to-X technologies, not only the emissions of CO_2 are reduced but also the domestic production of bioproducts (fuels and materials) is increased, reducing the associated imports. Consequently, the energetic independence of the country is further enhanced by investing on new technologies and by basing the energy strategy on domestic resources. Another important observation is the future role of electricity in the energy mix. Electricity production is prevalent in most of the considered energy scenarios, either being a direct service (e.g. electric mobility) or even an intermediate step for heating (e.g. heat pumps) and bioproducts (Power-to-X technologies).

Each of the indicative scenarios presented here tries to address a different perspective in a possible future Swiss energy system, namely nuclear phase-out, complete defossilisation, heating, mobility and resource price regulation to name a few. Evidently, the list of possible future scenarios is much larger and meaningful insights can be obtained regarding the role, interconnection and development of the carbon flows in the energy system, which in turn can be used to define the future energy strategy. The framework provided by the project could be used for scenario analysis for bodies addressing energy and environmental analyses including companies, associations and governmental organizations.

9 Publications and Presentations

This project was presented to:

- Z. Stadler, S. Moret, Th. Damartzis, B. Meier, M. Borasio, M. Friedl, F. Maréchal, “Carbon Flows in the Energy Transition”, Poster Session at expert talks Power-to-Gas, June 2018.
- Z. Stadler, S. Moret, Th. Damartzis, B. Meier, M. Borasio, M. Friedl, F. Maréchal, “Carbon Flows in the Energy Transition”, Workshop with SNF, SFOE, FOEN and Climeworks, Berne, November 28th, 2018.
- B. Meier, Z. Stadler, “Carbon Flows in the Energy Transition”, Presentation for working group on negative emissions from Stiftung Risiko-Dialog, Zurich, January 21st, 2019.
- Z. Stadler, “Kohlenstoffströme in einer nachhaltigen Energieversorgung”, Expertengespräche Power-to-Gas, Rapperswil, March 12th, 2019.
- Z. Stadler, S. Moret, Th. Damartzis, B. Meier, M. Borasio, M. Friedl, F. Maréchal, “Kohlenstoffströme in einer nachhaltigen Energieversorgung”, Tagung Bioenergieforschung in der Schweiz, SFOE Ittigen, May 9th, 2019.

This project will be presented at:

- Z. Stadler, S. Moret, Th. Damartzis, B. Meier, M. Borasio, M. Friedl, F. Maréchal, “Carbon flows in the Swiss energy transition”, 17th International Conference on Carbon Dioxide Utilization, June 23-27, 2019, Aachen, Germany.
- X. Li, Th. Damartzis, Z. Stadler, S. Moret, B. Meier, M. Friedl, F. Maréchal, ”Carbon flows in macro energy planning : The case of the Swiss energy system”, 12th European Congress on Chemical Engineering (ECCE), September 15-19, 2019, Florence, Italy.

About this project will be written in:

- Z. Stadler, B. Meier, M. Friedl, Th. Damartzis, S. Moret, X. Li, M. Borasio, F. Maréchal, “Die Kohlenstoffströme der Schweiz”, Aqua&Gas, to be published: July 2019.
- Journal publication (in development).

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11 Appendix

11.1 Product Specifications

Table A1. Specifications of the considered fuels and chemicals.

Energy Carriers	**Annual Demand (kt)**	**Price (CHF/kg)**	**LHV (kWh/kg)**	**Carbon Mass Fraction (%)**
Biogas				27
Coal			7.95	>99
Diesel			12.06	86
Gasoline				90
Hydrogen			33.32	0
Jet Fuel			11.94	82
LNG			12.50	75
Natural Gas / SNG			13.89	75
Oil			11.86	85
Chemicals	**Annual Demand (kt)**	**Price (CHF/kg)**	**LHV (kWh/kg)**	
Acetone	54.0	0.8	7.93	60
Acetic Acid	47.4	0.5	9.13	40
Benzene	0.02	0.6	11.16	15
Dimethyl Ether			8.02	65
Ethanol	36.3	1.4	7.42	52
Ethylene	8.2	1.0	13.11	86
Methanol	36.6	0.4	5.54	37
Phenol	36.5	1.1		77
Propylene	10.1	1.5	12.72	86
Styrene	1.2	1.4		92
Xylene	6.2	0.7	11.38	91
Plastics	**Annual Demand (kt)**	**Price (CHF/kg)**	**LHV (kWh/kg)**	
Polyethylene (PE)	208.2	1.7	12.81	85.7
Polyethylene terephthalate (PET)	95.8	1.1	12.81	62.5
Polyvinyl chloride (PVC)	84.3	1.1	5.00	38.4
Polypropylene (PP)	75.1	1.5	12.22	85.7
Polystyrene (PS)	56.2	1.5	11.17	92.3

Source: https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html

11.2 Electricity production

Technologies for the production of electricity are already defined in the EnergyScope model. If not stated otherwise, the values are taken from (Moret, 2017). Both renewable and non-renewable electricity supply technologies are considered.

Table A2. Parameters of the electricity production technologies.

Technology	Conversion Factors (Energy)	c_{inv} (CHF/kW)	c_{maint} (CHF/kW$_{th}$/y)	gwp_{constr} (kgCO$_{2-eq.}$/kW$_{th}$)	Lifetime	c_p
Nuclear power plant	Uranium: - 2.70 Electricity: + 1.00	5'175	110	707.9	60	0.8
CCGT	NG: - 1.59 Electricity: + 1.00	824	21.1	183.8	25	0.8
CCGT_CCS	NG_CCS: - 1.75 Electricity: + 1.00	1'273	30.2	183.8	25	0.8
COAL_US	Coal: - 2.04 Electricity: + 1.00	2'688	31.7	331.6	35	0.8
COAL_IGCC	Coal: - 1.85 Electricity: + 1.00	3'466	52.3	331.6	35	0.8
COAL_US_CCS	Coal CCS: - 2.38 Electricity: + 1.00	4'327	67.6	331.6	35	0.8
COAL_IGCC_CCS	Coal CCS: - 2.08 Electricity: + 1.00	6'045	73.9	331.6	35	0.8
PV		1'000	15.9	2'081	25	1
Wind		1'466	22.9	622.9	20	1
Hydro Dam		4'828	24.1	1'693	40	1
New Hydro Dam		3'437	2.89	1'693	40	1
Hydro River		5'387	53.9	1'263	40	1
New Hydro River		5'919	76.3	1'263	40	1
Geothermal		11'464	465	24'929	30	0.8

c_{inv} = investment costs, c_{maint} = maintenance costs, gwp_{constr} = global warming potential of the production of the technology unit, c_p = yearly capacity factor.

11.3 Heating and cogeneration technologies

Technologies for the production of heat are already defined in the EnergyScope model. If not stated otherwise, the values are taken from (Moret, 2017).

Table A3. Parameters of the heating and cogeneration technologies.

Technology	**Conversion Factors (Energy)**	c_{inv} **(CHF/kW)**	c_{maint} **(CHF/kWth/y)**	gwp_{constr} **(kgCO2-eq./kWth)**	**Lifetime (y)**	c_p
Industrial Cogeneration (Gas)	NG: - 2.17 $Heat_{HighT}$:+1.00 Electricity: 0.96	1503.6	98.9	1024.3	25	0.85
Industrial Cogeneration (Wood)	Wood: - 1.89 $Heat_{HighT}$:+1.00 Electricity: 0.34	1154.2	43.24	165.3	25	0.85
Industrial Cogeneration (Waste)	Waste: - 2.22 $Heat_{HighT}$:+1.00 Electricity: 0.44	3126.7	118.88	647.8	25	0.85
Industrial Boiler (Gas)	NG: - 1.08 $Heat_{HighT}$:+1.00	62.9	1.26	12.3	17	0.95
Industrial Boiler (Wood)	Wood: - 1.16 $Heat_{HighT}$:+1.00	123.0	2.46	28.9	17	0.9
Industrial Boiler (Oil)	Oil: - 1.15 $Heat_{HighT}$:+1.00	58.6	1.26	12.3	17	0.95
Industrial Boiler (Coal)	Coal: - 1.22 $Heat_{HighT}$:+1.00	123.0	2.46	48.2	17	0.9
Industrial Boiler (Waste)	Waste: - 1.22 $Heat_{HighT}$:+1.00	123.0	2.46	28.9	17	0.9
Industrial, direct electrical heating	Electricity: - 1.00 $Heat_{HighT}$:+1.00	354.9	1.61	1.5	15	0.95
District heating network, Heat Pump	Electricity: - 0.25 $Heat_{LowT\_DHN}$: + 1.00	368.2	12.81	174.8	25	0.95
District heating network, Cogeneration (Gas)	NG: - 2.50 $Heat_{LowT\_DHN}$: + 1.00 Electricity: + 1.25	1339.7	40.08	490.9	25	0.85
District heating network, Cogeneration (Wood)	Wood: - 1.89 $Heat_{LowT\_DHN}$: + 1.00 Electricity: + 0.34	1154.2	43.24	165.3	25	0.85
District heating network,	Waste: - 2.22 $Heat_{LowT\_DHN}$: + 1.00	3126.7	118.88	647.8	25	0.85

Cogeneration (Waste)	Electricity: + 0.44					
District heating network, Boiler (Gas)	NG: - 1.08 $Heat_{LowT\_DHN}$: + 1.00	62.9	1.26	12.3	17	0.95
District heating network, Boiler (Wood)	Wood: - 1.16 $Heat_{LowT\_DHN}$: + 1.00	123.0	2.46	28.9	17	0.9
District heating network, Boiler (Oil)	Oil: - 1.15 $Heat_{LowT\_DHN}$: + 1.00	58.6	1.26	12.3	17	0.95
District heating network, Geothermal	$Heat_{LowT\_DHN}$: + 1.00	1620.1	60.12	808.8	30	0.85
Decentralized, Heat Pump	Electricity: - 0.33 $Heat_{LowT\_Decen}$: + 1.00	525.5	22.48	164.9	18	0.285
Decentralized, Thermal Heat Pump	NG: - 0.67 $Heat_{LowT\_Decen}$: + 1.00	337.1	10.11	381.9	20	0.285
Decentralized, Cogeneration (Gas)	NG: - 2.17 $Heat_{LowT\_Decen}$: + 1.00 Electricity: + 0.96	1503.6	98.9	1024.3	20	0.285
Decentralized, Cogeneration (Oil)	Oil: - 2.33 $Heat_{LowT\_Decen}$: + 1.00 Electricity: + 0.91	1394.2	87.53	1024.3	20	0.285
Decentralized, Advanced Cogeneration (Gas)	NG: - 4.55 $Heat_{LowT\_Decen}$: + 1.00 Electricity: + 2.64	7734.0	154.68	2193.5	20	0.285
decentralized, Advanced Cogeneration (Hydrogen)	Hydrogen: - 4.55 $Heat_{LowT\_Decen}$: + 1.00 Electricity: + 2.64	7734.0	154.68	2193.5	20	0.285
Decentralized, Boiler (Gas)	NG: - 1.11 $Heat_{LowT\_Decen}$: + 1.00	169.3	5.08	21.1	17	0.285
Decentralized, Boiler (Wood)	Wood: - 1.18 $Heat_{LowT\_Decen}$: + 1.00	493.8	17.28	21.1	17	0.285

Decentralized, Boiler (Oil)	Oil: - 1.18 $Heat_{LowT\_Decen}$: + 1.00	152.1	9.12	21.1	17	0.285
Decentralized, Solar	$Heat_{LowT\_Decen}$: + 1.00	767.9	8.64	221.2	20	1
Decentralized, direct electric heating	Electricity: - 1.00 $Heat_{LowT\_Decen}$: + 1.00	42.7	0.19	1.5	15	0.285

c_{inv} = investment costs, c_{maint} = maintenance costs, gwp_{constr} = global warming potential of the production of the technology unit, c_p = yearly capacity factor.

11.4 Mobility and Transportation

Technologies for the demand in mobility and transportation are already defined in the EnergyScope model. If not stated otherwise, the values are taken from (Moret, 2017). The costs of the vehicles themselves are not considered, only the conversion efficiency.

Table A4. Parameters of the mobility and transportation technologies.

Technology	Fuel (kWh / pkm)
Tramway / Trolley	Electricity: - 0.17 Public Mobility: + 1.00
Bus / Coach (Diesel)	Diesel: - 0.27 Public Mobility: + 1.00
Bus / Coach (Hydiesel)	Diesel: - 0.18 Public Mobility: + 1.00
Bus / Coach (Gas)	NG: - 0.31 Public Mobility: + 1.00
Bus / Coach (Hydrogen)	Hydrogen: - 0.23 Public Mobility: + 1.00
Train (public transportation)	Electricity: - 0.09 Public Mobility: + 1.00
Car (Gasoline)	Gasoline: - 0.43 Private Mobility: + 1.00
Car (Diesel)	Diesel: - 0.39 Private Mobility: + 1.00
Car (NG)	NG: - 0.48 Private Mobility: + 1.00
Car (HEV)	Gasoline: - 0.25 Private Mobility: + 1.00
Car (PHEV)	Electricity: - 0.05 Gasoline: - 0.18 Private Mobility: + 1.00
Car (BEV)	Electricity: - 0.11 Private Mobility: + 1.00
Car (Fuel Cell)	Hydrogen: - 0.18 Private Mobility: + 1.00
Train (Freight transport)	Electricity: - 0.07 Mobility Freight Rail: + 1.00
Truck	Diesel: - 0.51 Mobility Freight Road: + 1.00
Plane	Jetfuel: - 1.00 Mobility Aviation: + 1.00

11.5 Imported Chemicals and Plastics (Data from SwissImpex)

Data from SwissImpex: https://www.gate.ezv.admin.ch/swissimpex/

- Table “Organic chemicals”
- Table “Plastics and Articles thereof”