Joint Activity Scenarios and Modelling

Decarbonization of Swiss energy systems in 2050: Integrated scenario analysis with the SES-EPFL model

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Contents

Abbreviations

BECC Biogenic Energy Carbon Capture.

BEV Battery Electric Vehicle.

CCUS Carbon Capture, Use and Storage.

CHP Combined heat and power.

COP Coefficient of performance.

DAC Direct Air Capture.

DEC Decentralized.

DHN District heating network.

EU European Union.

EUD End Use Demand.

GHG Green House Gases.

HP Heat pump.

IPCC Intergovernmental Panel on Climate Change.

IPESE Industrial Process and Energy Systems Engineering.

LCA Life Cycle Assessment.

MILP Mixed-Integer Linear Programming.

NG Natural Gas.

PV Photovoltaic.

SES Swiss Energyscope.

SNG Synthetic Natural Gas.

Chapter 1

Overview

In the context of striving for a sustainable society, participating countries in the Paris Climate Summit taking place in 2015 reached an agreement, declaring the objective of keeping the increase in global average temperature to well below 2°C above pre-industrial levels within this century; and further to pursue efforts to limit the increase to 1.5°C (**?**). In this background, European countries are pioneering the exploration of plausible pathways towards carbon mitigation: the Netherlands announced all Dutch cars must be emission-free by 2030 (NLTimes, 2017); Germany planned to phase out the coal power plants by 2038 (Rinscheid and Wüstenhagen, 2019); France enacted a mid-term strategy to reduce the proportion of energy powered by fossil fuels by 40% in 2030. In general, European Union (EU) has committed to realize carbon neutrality in 2050 according to the law enacted in EUROPA (2018).

In terms of Switzerland, there is a host of energy policies that range from rules for market liberalization to programs for energy conservation, subsidies for renewables, and regulations for Green House Gases (GHG) reduction (Markard et al., 2016). In 2011, the Swiss government and parliament decided to phase-out nuclear following the Fukushima nuclear accident, and to stimulate energy efficiency and the use of renewable energies instead. As a consequence, the government developed the Energy Strategy 2050, setting long-term targets for the reduction of energy consumption (54% reduction until 2050) and the expansion of renewable electricity generation and combined generation of power and heat. With respect to climate policy, Switzerland undertook a commitment to halve its greenhouse gas emissions versus the 1990 level by 2030. To accomplish this, the existing Federal CO2 Act has to be revised for the period beyond 2020. The corresponding bill is currently being debated in Parliament. In 2019 the Swiss Federal Council resolved that, as of 2050, Switzerland is to reduce its net greenhouse gas emissions to zero (net zero emissions target) (SFOE, 2020). This declares it is aiming to meet the internationally agreed goal of limiting global climate warming to a maximum of 1.5°C versus the pre-industrial period. To realize this objective, two methods are generally considered:

- mitigation of carbon sources: predominately translated by the massive penetration of renewable resources, and efficiency improvement for carbon intensive areas;
- reinforcement of carbon sinks: in either natural way, such as afforestation and reforestation, or artificial way, typically the deployment of CCUS technologies.

Recently, large application of carbon capture technologies, particularly Biogenic Energy Carbon Capture (BECC), has gained prominence with the witnessed rise of advocacy over years, since biomass is explicitly indicated as carbon-neutral from Life Cycle Assessment (LCA) perspective by the Intergovernmental Panel on Climate Change (IPCC), shedding light on the carbon neutral society by applying BECC for creating negative emission. In spite of increasing attention on the decarbonization, the majority of current researches focuses principally on the improvement of standalone processes within limited boundaries, for instance in an industrial site level, rendering a lack of holistic view on the interactive impacts on the whole energy systems. Another challenge is arising with increasing Carbon Capture, Use and Storage (CCUS), in particular carbon re-utilization, which is likely to release back the captured carbon into the atmosphere, resulting in carbon flow loops as long as the corresponding carbon products are not chemically stable and non-releasable, typically recyclable plastics. The loop issue is even more tough to be tackled taking into consideration the double nature of biomass as both carbon source and sink. In addition, current studies have paid limited attention on the relationship of carbon capture and renewable development which cannot be simply regarded as *synergistic* or *mutually exclusive* due to the intrinsic complexity of the interactions between resources and technologies. A simple example is, more renewables would result in decreasing fossil carbon sources, thus limiting the scale of carbon capture deployment.

Therefore, it is necessary to analyze the trade-offs rooted in energy systems, from the aspects of energy supply-demand and carbon flows by distinguishing major carbon categories and identifying various energy and carbon sources and sinks. It allows to discover the potential opportunities for breakthrough, especially with respect to certain key technologies, and quantify the carbon footprints in order to optimize the circular economy associated to a net zero emission society, in favor of policy-making for sustainable development in long terms. For this purpose, this report is organized in the following chapters:

- Chapter 2 describes the modeling methodology, and highlights the recent updates;
- Chapter 3 introduces major assumptions and data used, followed by scenarios definitions;
- Chapter 4 illustrates and analyzes the modeling results, which involves two parts:
  - nominal results for typical scenarios
  - uncertainty test results
- Chapter 5 concludes by summarizing the main contributions and limits of the model, and presents the authors' perspectives for further research.

Chapter 2

Model description

This research is conducted based upon Swiss Energyscope (SES), a bottom-up energy system model in favor of decision making for techno-economic and ecological optimization. Compared to other existing energy models, which are often proprietary, computationally expensive and mostly focused on the electricity sector (Limpens et al., 2019), Energyscope optimizes both the investment and operating strategies of an entire energy system (including electricity, heating and mobility) by taking a “snapshot” for a given year. In this study, 2050 is chosen as the objective time horizon. In spite of various versions of Eneregyscope, this report relies on the monthly granularity. Apart from its effectiveness in optimization algorithm in terms of convergence speed that facilitates to uncertainty test, the monthly model is commonly used in long terms planning with, on one hand, necessary time resolution for ensuring the plausibility of results, and on the other hand, diminishing unavoidable intense stochasticity spread in more refined data inputs. The optimization carried out by this study was based upon AMPL (A Mathematical Programming Language) with CPLEX as the solver.

2.1 Modeling methodology

SES is a Mixed-Integer Linear Programming (MILP) optimization platform. All decision variables hereafter are marked in **bold** format. The objective function of the Energyscope is to minimize the annual total cost ($\mathbf{C_{tot}}$) expressed by the sum of the annualized CAPEX ($\mathbf{C_{inv}}$), the annual variable OPEX ($\mathbf{C_{op}}$) for the resource purchase and the annual fixed OPEX, namely maintenance cost ($\mathbf{C_{maint}}$) shown in Equation (2.1).

$$\min \mathbf{C_{tot}} = \min\Big(\tau(i,n(j))\sum_{j\in\mathscr{E}}\mathbf{C_{inv}}(j) + \sum_{j\in\mathscr{E}}\mathbf{C_{maint}}(j) + \sum_{r\in\mathscr{R}}\sum_{t\in\mathscr{T}}\mathbf{C_{op}}(r,t)\,t_{op}(t)\Big) \tag{2.1}$$

where the sets $\mathscr{E}$, $\mathscr{R}$ and $\mathscr{T}$ represent the technologies, the resources (renewables and non-renewables as well as electricity import) and the time periods (twelve months within one year) respectively. $t_{op}(t)$ denotes the duration of the period t. The investment cost $\mathbf{C_{inv}}(j)$ is annualized by a factor $\tau(i,n(j))$ expressed as:

$$\tau(i,n(j)) = \frac{i(1+i)^{n(j)}}{(1+i)^{n(j)}-1} \tag{2.2}$$

where i represents the interest rate assumed to be 2.215% and $n(j)$ stands for the expected lifetime for the technology j. The energy flows from resources $\mathscr{R}$ to demands $\mathscr{D}$ is expressed as by the Equation 2.3, with the transitional matrix reflecting the energy conversion efficiency of the technologies in consideration that were reported in Bauer et al. (2020), Stadler et al. (2019).

$$\left[\ldots\mathscr{R}_i\ldots\right]\left[\begin{array}{c} \\ \ldots\mathscr{E}_{i,j}\ldots \\ \\ \end{array}\right] = \left[\ldots\mathscr{D}_j\ldots\right] \tag{2.3}$$

Apart from the supply-demand balances, other constraints including the availability of resources, minimal and maximal limits of installed capacity for different technologies, power grid capacity ceiling, CO2 limits, and so on, were formulated in Moret et al. (2017). Key parameters for energy demands and technologies will be introduced and explained in the following chapters.

2.2 Energy demands

2.2.1 Estimation on energy demands in 2050

Energy End Use Demand (EUD) in this model is defined as the final energy demand other than the energy carrier. For instance, the passenger mobility demand is of unit Mpkm (Million passenger kilometers) other than GWh of diesel or other fuels/electricity. This approach allows for switching towards more techno-economically efficient supplying alternatives for a given EUD. This study adopted the electricity and heat demands values available at JASM (2020) (ref scenarios), which were resulted from historical data and assumptions on macro-economic factors, such as GDP and population (Marcucci et al., 2020). Mobility demands keep the same as reported in Stadler et al. (2019). In resume, the EUD in 2050 in different sectors and in various supplying forms are summarized in Table 2.1. Specific chemicals and plastics demands are available in the appendix A.1.

Table 2.1: Swiss energy demands projection in 2050 (JASM, 2020, Stadler et al., 2019)

EUD	**Residence** [GWh]	**Commerce** [GWh]	**Industry** [GWh]	**Mobility** [Mpkm] or [Mtkm]
Electricity	11792	13528	11715	-
High temperature heat	-	302	18891	-
Low temperature for space heating	38252	11571	2978	-
Low temperature for hot water	7593	2655	596	-
Passenger mobility	-	-	-	140300[a]
Freight mobility	-	-	-	39700[b]

[a]Unit: Mpkm, million passenger kilometer
[b]Unit: Mtkm, million ton kilometer

2.2.2 Energy efficiency

Energy efficiency plays an essential role in the Swiss energy transition that is explicitly indicated in the Energy Strategy 2050 (DETEC, 2020). In order to quantify the impact of efficiency improvement on Swiss energy systems, the three energetic giants - industry, household and transport - are analyzed respectively in this section.

Industry

Industrial Process and Energy Systems Engineering (IPESE) group has conducted research desegregating Swiss industry into sub-sectors including steel, paper, food & beverage, cement and so on based upon innovative system integration approaches for exploring energy saving potential in Switzerland. Detailed results are reported in Zuberi et al. (2020), which estimates 24% (ranging from 12%-42%) saving potential for process heat demand and 7% (ranging from 1%-28%) for electricity demand respectively for the entire industry of Switzerland in 2050 compared to 2016.

Building

The energy saving potential for Swiss buildings is regarded immense: according to Weinmann (2020), a poorly insulated building can consume up to 300 kWh/a per square meter, while a building built according to the Minergie standard requires no more than 10% of that value. Streicher et al. (2020) researched the impact of building renovation on the energy saving, where the current Swiss building stocks were assessed by type, construction year, locality, typology, area and various renovation methods, concluding an estimated 3.4 MCHF renovation cost for achieving 1 GWh/a energy saving in households. This value is obtained from the scenario "improve" available in the database JASM (2020).

With respect to the total saving potential, Either and Pauli (2014) in the white paper on building prospect for Switzerland declared a 50% saving potential by renovation in 2050 with respect to 2010. This value is reckoned relatively plausible taken into account the rapid decrease by 19.1% in residential space heating for 2019 with respect to 2010. In our model, the energy saving potential for all buildings in Switzerland in 2050, including space heating and hot water, is set as a parameter ranging between 0-30% compared to today's value, representing the large uncertainty of renovation.

Transport

The efficiency improvement in transport depends considerably on the penetration of electric vehicles, which is of higher efficiency and could mitigate the carbon emission considerably as long as the electricity sources are green. In terms of passenger mobility, Battery Electric Vehicle (BEV) accounts for merely 2-3% in the market share in 2017 according to OFS (2018), which is expected to rise to 70% in 2050, despite a large uncertain range 50-80% given by de Haan et al. (2013). Some experts envisage 100% penetration of electric vehicles is even not impossible in the presence of well planned infrastructure. In this model, we assume 60-100% uncertainty range for the share of electric vehicles in passenger mobility.

As to freight mobility, increasing penetration of trains is expected due to its high efficiency. Taken into account the limitation of trains for certain regions and within cities, trucks are supposed to hold at least 20% share in the freight mobility.

In resume, the parameters for energy efficiency used in this model are summarized in Table 2.2.

Table 2.2: Assumption on energy sectorial saving potentials in 2050 with respect to 2015-2019

Sector	Building	Industry		Transport
	Heat	Heat	Elec	Electrification
High	30%	42%	28%	100%
Low	0%	12%	1%	60%

2.3 Technologies

2.3.1 Renewables

Photovoltaic (PV)

PV is currently a mature technology, and many researchers are optimistic on its large deployment in the future. However, almost all current research focuses merely on roof and wall based PV panels, which may ignore other possibilities, such as the installation of PV panels along the guardrail in highways. Despite a question-mark on the techno-economic survivability of these innovative approaches which require other dedicated projects to demonstrate, the value we use in this model, 25 TWh/a, is regarded as plausible by the majority of recent studies with an uncertain range from 20 - 50 TWh/a, given the physical limit 67 TWh/a considering all eligible roofs and walls are equipped with PV panels, estimated by OFEN.

Wind

Due to the inland geographical factor, wind development in Switzerland is only based upon onshore wind farms. As another important intermittent technology, wind potential is regarded as 4.3 TWh/a in 2050 taking into account both technical feasibility and social acceptance conducted by IEA (2018). Compared with PV, the uncertainty range of wind in terms of absolute value is less significant which is assumed to be between 1.5 - 7 TWh/a.

Geothermal

The utilization of geothermal energy is modeled from two aspects: shallow geothermal (approx. <300m) and deep geothermal (approx. >1000m). By introducing Heat pump (HP), especially ground source heat pump, the Coefficient of performance (COP) of the former commonly ranges from 300%-600%, while the latter could be directly used for heat and power generation due to its relatively high temperature (>100°C).

For **shallow geothermal**, the total installed capacity amounted to 2 GW in 2017, which embraced an indubitable success with overall annual growth rates up to 12%. Shallow geothermal could be used for both district and decentralized heating. Despite a few concerns on the impact of shallow geothermal deployment on water protection (Link et al., 2019), there are no obvious environmental-technical barriers to the further development of this technology. Therefore, it is assumed in this model no explicit physical limit for the utilization of heat pumps for low temperature heat supply.

Concerning **deep geothermal**, it is assumed only available for District heating network (DHN) and power generation, implying decentralized heating on a small scale by deep geothermal is not included. The theoretical potential for direct heat supply and for power generation is considered very huge, estimated to 600000 TWh_{th} (Hirschberg et al., 2015) beneath Switzerland when cooling the 1.5 km thick rock layer between 4 and 5.5 km by 20°C. The major obstacle for a large application is the limited knowledge of the deeper subsurface and the impact of temperature drop on geology. More realistic estimates on the technical and economic potential are around 1-20 TWh_{el}/a. SFOE estimated 4.4 TWh as potential for geothermal power in 2050 scenario, which is also taken by this study. It should be noticed that this value does not include the direct heat that deep geothermal could deliver, which is assumed less than 30 TWh/a in this model.

DHN

District heating is not a technology but rather composed of a bunch of technologies, such as large gas boiler and heat pump. It amounted to 5389 GWh in final consumption 2018 (SFOE, 2019), accounting for approx. 8.7% of low temperature heating demand. Either and Pauli (2014) estimated 38% DHN share in 2050. In this model, we adopted this value as the nominal value for district heating, with uncertainty range up to 75%. Additionally, a 5% heat loss is assumed for DHN heat supply.

Biomass and waste

Biomass In this model, biomass is divided into two major categories: woody and non-woody biomass, each including multi-subcategories: take non-woody biomass for instance, it is composed of manure, sewage sludge, agriculture organic crops, etc. Without specification, this report takes values from Stadler et al. (2019), with small updates based upon Guidati et al. (2020). By aggregating all sub-categories, the woody biomass potential is estimated to be 15.3 TWh in 2050, and 12.5 TWh for non-woody biomass. It is highlighted that these values refer merely to the sustainable potential of Swiss biomass stocks, implying the biomass for non-energy usage (e.g.for furniture), is not included.

In general, the utilization of biomass in energy sectors encompasses two directions: direct combustion in thermal plants or households for power and heat; or valorization to fuels (biofuels), commonly gas and liquids, facilitating transportation and flexibility in utilization. Gasification, anaerobic digestion, Fischer-Tropsh (FT) processing, and hydrothermal gasification, etc., are all common approaches for effective utilization of biomass according to their associated specificity in each sub-category. The technologies and corresponding data we adopted concerning biomass in this model were reported in Bauer et al. (2020).

Waste Waste is a man-made resource. Based upon Guidati et al. (2020), the waste contributing to energy systems could be categorized into two parts assuming no import and export in 2050: municipal waste and other fraction waste, where the non-biogenic parts account for 60% and 50% respectively in the two categories. By multiplying the shares with corresponding energy potentials for each category, we estimate that the non-biogenic waste in 2050 amounts to 10833 GWh and the biogenic waste 8917 GWh, including the green waste 305 GWh.

In this model, we assume a constant waste generation speed over months, and no accumulation of waste, implying waste disposal takes place within the same period as it is generated.

2.3.2 Storage

Long terms storage

The long terms storage here refers to seasonal storage. Two technologies are considered in this model: hydro storage and chemical storage. Updated from the previous report (Stadler et al., 2019), non-gaseous (solid and liquid) bifuels which are produced domestically, are assumed storagable in this model with unlimited storage capacity, as well as negligible cost and energy penalty. This approach helps to avoid the enforced immediate consumption imposed on production that the majority of energetic models adopt, ensuring a higher degree of freedom for optimization solver and adapting better to reality.

Concerning the gas-phase chemical storage, pipeline storage, high pressure steel tank and underground storage are the most promising methods. For **pipeline** storage, Table 2.3 gives an estimation of energy storage potential in Switzerland for Natural Gas (NG) and hydrogen based upon current NG grid infrastructure. The results show that the pipeline capacity for either natural gas or hydrogen storage seems very limited compared to the annual NG consumption today (30-40 TWh). Additionally, hydrogen storage potential is merely as much as 25% of natural gas in terms of energy. CO2 storage by NG grids is not considered since at the pressure 70 bar and ambient temperature 25°C, CO2 is in the liquid phase, which is not recommended by IPCC out of techno-economical consideration. Commonly the ideal pressure for CO2 transportation by pipeline is either larger than 96 bar in the dense state, or lower than 48 bar in the gas phase at ambient temperature.

Table 2.3: Estimation on the maximal energy storage capacity based upon existed NG grids in Switzerland.

	Length [km]	**Pressure**[a] [bar]	**Pipeline diameter** [cm]	**Density**[b] [kg/m3]	**LHV** [kWh/kg]	**Energy** [GWh]
Natural gas						
Transportation	2253	70	71.12	50.1	13.89	622.4
Distribution	17200	5-20	10.16	3.26-13.4	13.89	6.31-26
Hydrogen[c]						
Transportation	2253	70	71.12	5.46	33.3	162.9
Distribution	17200	5-20	10.16	0.41-1.6	33.3	1.88-7.53
Ref	(SFOE, 2016)	(Erdgas)	(Erdgas)	Coolprop		

[a] Pressure in NG transportation varies commonly between 65-75 bar in Switzerland, depending on different operators, the majority: 70 bar. Distribution pressure varies according to locations, the majority is around 5-20 bar for Swiss major grid companies.

[b] Density at 25°C and corresponding pressure level based upon calculation in Coolprop.

[c] For estimation of hydrogen storage capacity in networks, assume taking the same infrastructure as natural gas at the same pressure level without consideration of other technical feasibility.

Table 2.4: Parameters on infrastructure for chemical storage. (Gorre et al., 2018, Leeuwen and Zauner, 2018)

	Storage method	**CAPEX**[a] [€/kWh]	**OPEX (Maintenance)** [€/kWh]
Hydrogen	Salt caverns	0.036	0.00072
	High pressure steel tanks[b]	33.33	0.49995
Natural gas	Depleted natural gas reservoir	0.009	0.00018
	Salt caverns	0.012	0.00024
	High pressure steel tanks[b]	10.78	0.2156

[a] The investment cost is based upon the maximal volume of storage, multiplied by the specific investment cost.

[b] Based upon 100 €/m^3 capital expenditures; not integrated into Energyscope since it is commonly used for short-terms storage.

For **cavern** and **high pressure tanks** storage, the project STORE&GO under EU-H2020 conducted a survey based upon existed cavern storage in several European countries, and the major results are summarized in the Table 2.4. Seasonal storage in an underground reservoir is nothing new: GAZNAT, one of the major gas suppliers for Switzerland, declared owing storage capacities in salt cavities in the Bourg-en-Bresse region of France which are already in operation; the largest aquifer reservoir in Chemery, France, can hold 7 billion m^3 of natural gas, which is equivalent to twice Switzerland's annual gas consumption. Therefore, it is more precisely a matter of where to store (domestically or in foreign counties) rather than the necessity to store. From the results, high pressure tank costs approx. 100 times as that of underground storage for both hydrogen and NG, and as a result, is not regarded as a mainstream storage method in the future in spite of some applications on limited scale.

Short terms storage

Short terms storage refers to the processes within weeks, hours, seconds and even milliseconds, typically represented by batteries. It should be highlighted that, batteries are not supposed to replace the role of seasonal storage technologies since the former can only store energy for a short duration, at maximal weeks. As soon as the charging source is removed, they start to lose the charge. Therefore, we assume the battery serves only for daily regulation without impact on the seasonal energy supply-demand balance. In this study, the behavior of battery is not specifically modelled due to the time resolution incompatibility; however, in order to estimate the required battery capacity for short-term storage, we integrated the results from a distinct study in JASM project (Gupta et al., 2020), which analyzed the relationship between battery and PV installation capacity, based upon Swiss power grids and geographical analysis, so as well to ensure supply security. We apply linear regression on these data and obtained an empirical approximation of the required battery capacity y [GW] as a function of PV installed capacity x [GW] expressed by the Formula 2.4:

$$y = 0.2848x - 3.5319 \ (x \geq 12) \tag{2.4}$$

2.3.3 Negative emission technologies

Carbon capture

Carbon capture is becoming unarguably essential in the context of decarbonization. Here we examined carbon capture technologies in different sectors, including power/thermal plants, fuel production, as well as important manufacturing industries. Key parameters for these considered sectors are listed in Table A.1 (see Appendix). Coal plants are not taken into account in this study. By comparing the data, the deployment of carbon capture on biomass-based technologies appears economically and energetically predominant to conventional fossil-based energy industries, which releases a benign signal for potential further development, particularly contributing to creating negative emission.

Carbon sequestration

CO2 sequestration refers to store the captured CO2 underground. It is proved to be a safe operation if storage sites are properly selected and managed thanks to a couple of decades injecting CO2 in deep underground formations all over the world. In terms of Switzerland, studies by Chevalier et al. (2010) reflect it has deep saline aquifers that could store 2.6 billion tons of CO2. However, this value is of large uncertainty, and there is little knowledge about specific sites suitable for CO2 storage. Such sites need to fulfill a number of criteria: CO2 injectivity tests need to confirm the presence of saline aquifer/reservoir rock that occurs below associated seals provided by tight cap rocks. Reservoir seal couples need to be confirmed at depths between 800 and 2500 m. The temperatures in these rocks should be determined by low geothermal gradients (°C per km depth) giving rise to temperatures between 20-70 °C (Fasihi et al., 2019). It should be highlighted that this depth may overlap with available deep geothermal sources. Additionally, the physical properties of the respective rock formations, their permeability and porosity, their injectivity and so on are also factors that govern the amount of CO2 that can be ultimately stored.

Compared to other European countries, the CCS Readiness Index[1] for Switzerland in 2019 was graded to be 17/100, ranking among the lowest readiness European countries for CCS. It is therefore critical to coordinate the expansion of CC technologies and CO2 infrastructure development. Further research on geological feasibility is necessary and even urgent in order to determine storing within Switzerland or connecting to the European CO2 network. This study will result in a range indicating the amount of CO2 that needs to be sequestrated for Switzerland in order to realize carbon neutrality.

Carbon utilization

CO2 can be regarded as a carbon source, a raw material for the production of synthetic fuels and various chemicals/plastics. This is realized through a number of considered CO2-to-X processing technologies, typically with the participation of hydrogen. If the hydrogen stemming from electricity, the corresponding fuels are named efuels. The synthetic fuels in this model include Synthetic Natural Gas (SNG), diesel and gasoline, and the considered chemicals/plastics are reported in Bauer et al. (2020).

[1] CCS Readiness Index was initiated by the CO2RE (2020) database in Global CCS Institute, actively monitoring the CCS deployment, which tracks a country's requirement for CCS, including policy, law, regulation and storage resource development. It ranges from 0-100 where the higher, the more mature for CCS. For instance: Germany 50, France 44, Norway 65 in 2019.

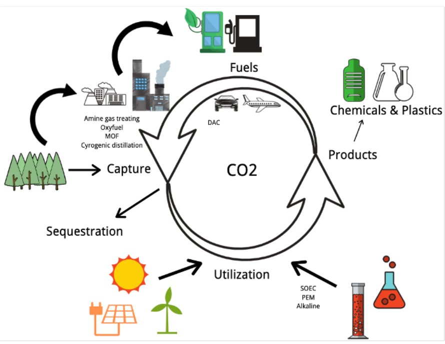
2.4 Carbon flow

As stated, carbon flows in high penetration of biomass and CO2-to-X technologies are complicated in the presence of interconnected loops. Figure 2.1 depicts the conceptual carbon flows in the system: carbon sources are divided into biogenic and non-biogenic parts: both could be used to produce electricity and heat, or converted to other fuels, for instance bio-diesel. By applying carbon capture technologies, a part of emission could be sequestrated underground, or reused in the presence of excessive renewable intermittent energy supply to synthesize e-fuels or other chemicals/plastics, such as polyvinyl chloride (PVC). The latter are stable in the sense that no further emission is expected if recyclable, while the former are supposed to be reused, e.g by a car, leading to CO2 emission to the atmosphere again, which is assumed only capturable by biomass or Direct Air Capture (DAC). In resume, if the energy system is a black box with carbon inputs and emission outputs, then:

- biogenic carbon sources will create **at most** zero emission; furthermore, negative emission with carbon capture and sequestration;
- non-biogenic carbon sources will create **at least** zero emission, in the presence of carbon capture and sequestration. In reality, the emission will always be positive since the capture efficiency is not able to reach 100% technically.

Different from the majority of models which simply set the carbon emission of biomass as net zero, the approach in SES, taking both positive and negative emission, allows for tracking the whole carbon flow chain and in the meanwhile avoids the difficulty of artificially distinguishing the biogenic or non-biogenic carbon sources in specific processes, for example in waste incineration where both biogenic and non-biogenic carbon sources exist. The carbon balance in SES is handled by the CO2 layers (see Figure 2.1), which behave as tanks with incoming carbon flows from various sources and outgoing flows to different locations. The following list summarizes the CO2 layers defined in the MILP model:

- CO2_A: the carbon emission from carbon intensive fields, such as a cement factory. This amount of carbon emission is capturable by applying conventional carbon capture technologies, e.g. pre-combustion capture, post-combustion capture etc. In Energyscope, all centralized emissions are computed into this category.
- CO2_C: the captured carbon, which is assumed to either be used or stored; in this level, CO2 storage could be further categorized as:



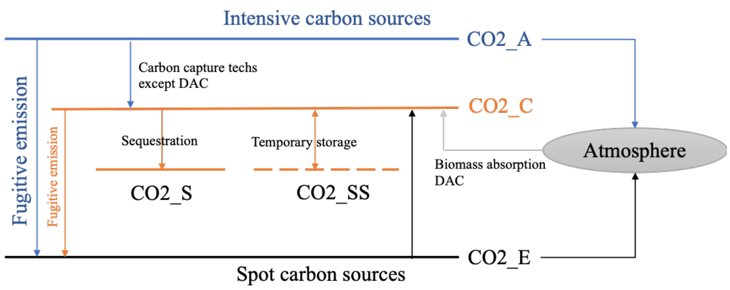


Figure 2.1: Circular carbon flow modeling **(A)**: carbon flow concept, **(B)**: CO2 layers in SES.

  - CO2_S: sequestration, where the CO2 is buried into underground formation and cannot be reused;
  - CO2_SS: temporary storage, implying the CO2 is capable of being used later.

- CO2_E: in contrast to CO2_A, the CO2_E refers to the carbon emissions from non-concentrated spot sources, e.g. a car or a household wood boiler. Apart from that, fugitive emissions from conventional carbon capture technologies are also included into CO2_E, as well as those stemming from construction periods. These emissions are not supposed to be mitigated without biomass photosynthesis or DAC. In Energyscope, all emissions stemming from Decentralized (DEC) technologies belong to this category.

Figure 2.1 illustrates the relationship of the CO2 layers defined in the model. All technologies in SES are linked to a/several CO2 layer(s) with corresponding emission factors. Following one carbon flow cycle, such as wood: when it is converted, e.g. to synthetic fuels, part of its carbon goes to form the hydrocarbon molecules, and the other part is released to atmosphere (CO2_A) that can be captured in place and converted to CO2_C to be treated by following sequestration or re-utilization processes. If sequestrated, negative emission will be realized; if reused and not captured anymore, the associated positive emission will be compensated by the negative emission in wood formation (negative CO2_E), resulting in net zero emission. Following this logic, the total emission (TE) of the energy system is thus expressed as the sum of the carbon emissions in the layers CO2_A and CO2_E, which is subject to a ϵ-control representing the decarbonization objective in 2.5, where $\mathbf{F}(j)$ denotes the output for technology j in the time period t, and η reflects the emission factors for this technology to a certain CO2 layer k.

$$TE = \sum_{\substack{j \in \mathscr{E}, \\ k \in CO2\_A \cup CO2\_E, \\ t \in \mathscr{T}}} \mathbf{F}_t(j)\eta(j,k)\,t_{op}(t) \leq \epsilon \tag{2.5}$$

Chapter 3

Scenario definition and implementation

The definition of decarbonization plays a crucial role in decision-making but commonly is described murkily and varies frequently in literature. From the authors' perspectives, it involves the following aspects:

- spatiality and temporality: it refers to the geographical boundary, in particular with respect to import and export. One disputable question is where to allocate the cross-border emissions, e.g. the emission stemming from mining for natural gas, on the country of consumption, or country of origin. Additionally, for some resources, typically electricity, the carbon intensity varies over periods and origins. Tab. A.3 presents the monthly cross-boundary import quantity and associated carbon intensity of electricity expressed as gCO2-eq./kWh, as well as purchase price from Germany, France, Austria and Italy respectively in 2019.
- modeling boundary: in energy sectors, there is no agreement for the moment on the allocation of the emissions from aviation, which consumed 21 TWh/a jet fuel in 2017 (Stadler et al., 2019). Outside the energy system, some other sectors, such as agriculture, emits around 6-7 Mt CO2-eq. in 2018 (fédéral de l'environnement OFEV).

In this model, we account for specifically the emission from cement manufacturing due to the process $CaCO3 \rightarrow CaO + CO2$. In order to avoid double counting the emission, only the direct emission from the calcination of limestone is taken into account independently, which amounts to 1.62 Mt CO_2 per year in Switzerland (Zuberi and Patel, 2017) and is assumed to be distributed uniformly over all periods. The remaining emission (indirct emission) from the process of fuel utilization for heating the kiln and effecting the clinkering reactions (Bui et al., 2018) etc, is counted within industry heat demand. As a result of the policy to phase out nuclear before 2035, this model does not deal with nuclear, the same for coal. As to the import, according to EUROPA (2018), the EU is supposed to realize carbon neutrality by 2050. As a result, the carbon intensity by the electricity import could be regarded as quasi-zero in an optimistic perspective. In order to reflect the possible discrepancy due to unfulfillment, we assume the carbon intensity of electricity import ranging between zero and 25% of today's value. The carbon intensity of imported hydrogen depends on its origin: natural gas reforming dominates the hydrogen production market today, which is not expected to develop in the absence of CCS (FCH, 2019), leading to negligible carbon intensity in hydrogen; additionally, electrolysis and wood gasification are becoming increasingly promising in competing with the fossil-based hydrogen production industry. For instance, electrolyzers are available on small scale (< 1 MW) today, with demonstration projects for larger scales (up to 10 MW) are underway. In either way, the carbon intensity of hydrogen import could be regarded as zero in 2050 due to increasing GHG limitation. Aviation is not taken into consideration due to the lack of explicit international convention on its emission allocation.

For implementation of scenarios, we firstly focus on a scenario with the nominal values reported in previous chapters. Without specification, the decarbonization scenario hereafter implies -6 Mt CO2/a without any fuel import (chemicals and plastics exc.). Then we perform uncertainty tests on three scenarios in order to explore:

- the uncertainty impact from energy efficiency improvement;
- the uncertainty impact from the production potentials of key technologies;
- the uncertainty impact from energy importation.

Chapter 4

Model results

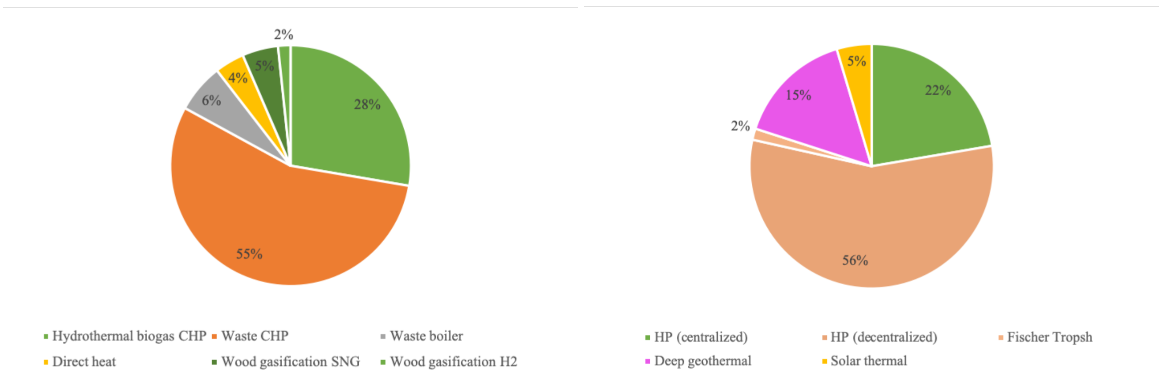
This chapter presents the main results obtained from the integrated system modeling, with some discussion in the end on the key discoveries and modeling limits.

4.1 Results for the decarbonization scenario

4.1.1 Energy audit

Heat supply

From the optimization results, the process heat supply in 2050 achieves 15.1 TWh, and the low temperature supply for space heating and hot water 64.9 TWh. The corresponding shares of supplying technologies are presented in Fig.4.1. In terms of process heat, the greatest contributor, waste, accounts for approx. 60% in the heat supply, followed by cogeneration of biogas around 28%. Direct heater by electricity plays a limited role taking 4% of the heat mix. For space heating and hot water supply, heat pumps become dominant accounting for 78% in the low temperature supply mix. Deep geothermal achieves its estimated limit contributing 10 TWh heat. By summing up the shares of centralized heat pump and deep geothermal heat, the district heating share amounts to 38%, which



(a) Process heat supply

(b) Space heating and hot water supply

Figure 4.1: Modeling results: heat supply. (a) Process heat; (b) Space heating and hot water.

matches exactly its estimated potential presented in 2.3. In this regard, large development of district heating would contribute techno-economically to the energy transition.

The above analysis reveals the trend of centralization in heating supply. This is mainly due to the competitiveness of a centralized system in terms of the energy efficiency and marginal cost decrease per kWh energy produced compared to a decentralized one. Shallow geothermal associated with heat pumps and deep geothermal can be regarded as the most promising technologies in heating supply towards decarbonization.

Electricity

Electricity production amounts to 78 TWh/a which is almost full renewable except for a small part from non-biogenic waste. Storage is not included in this value. The monthly variation of electricity production by technologies is presented in Fig.4.2. Hydro power (dams + rivers) still dominates the electricity mix and accounts for around 47%, followed by PV amounting to 32%. Wind and geothermal power reach their estimated limits 4.3 TWh/a and 4.4 TWh/a respectively. Other contributions come from Combined heat and power (CHP) of waste and biomass. Apparent seasonality is reflected from the renewable production variation, particularly PV panels, which outputs 4 times more at the peak in summer than the trough in winter, while wind generates twice the amount of power in winter than in summer. Geothermal and biogas combustion take place principally in cold periods with high energy demands: all these create opportunities of seasonal storage that will be discussed later. Waste incineration keeps almost constant the whole year with a slight decrease in summer.

In terms of power consumption apart from demands, Fig. 4.3 summaries the major electricity consumers, where the heat pumps and electric vehicles take the largest parts, amounting to 29 TWh/a. This value is close to the total annual production from PV and wind. Around 3.2 TWh/a power is used in electrolysis for hydrogen production, and the remaining parts mainly go to various industrial sectors. Compared to the EUD for electricity, approx. 40 TWh/a additional power is required for sat-

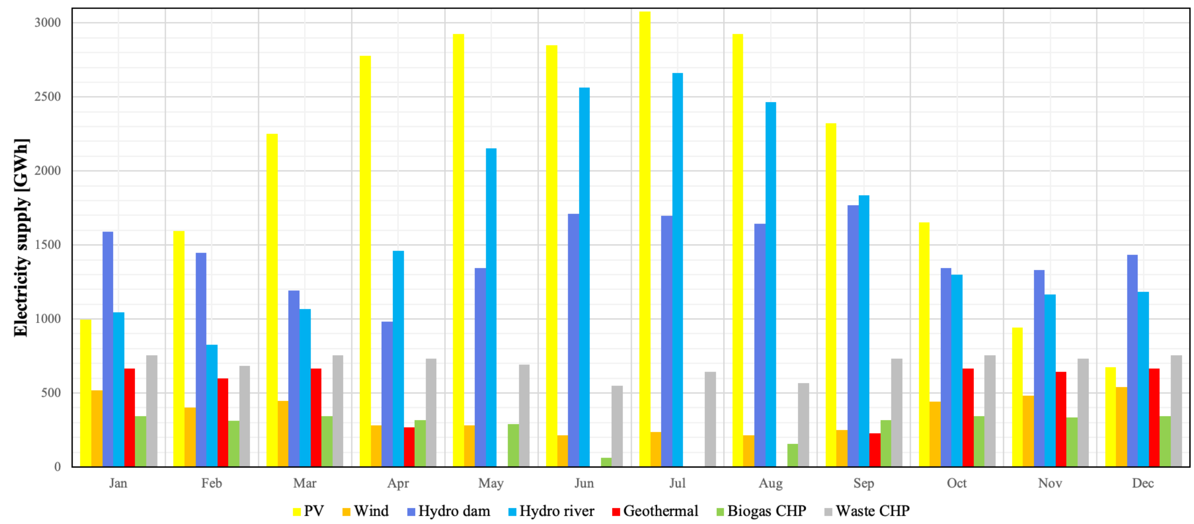


Figure 4.2: Monthly electricity supply by technology

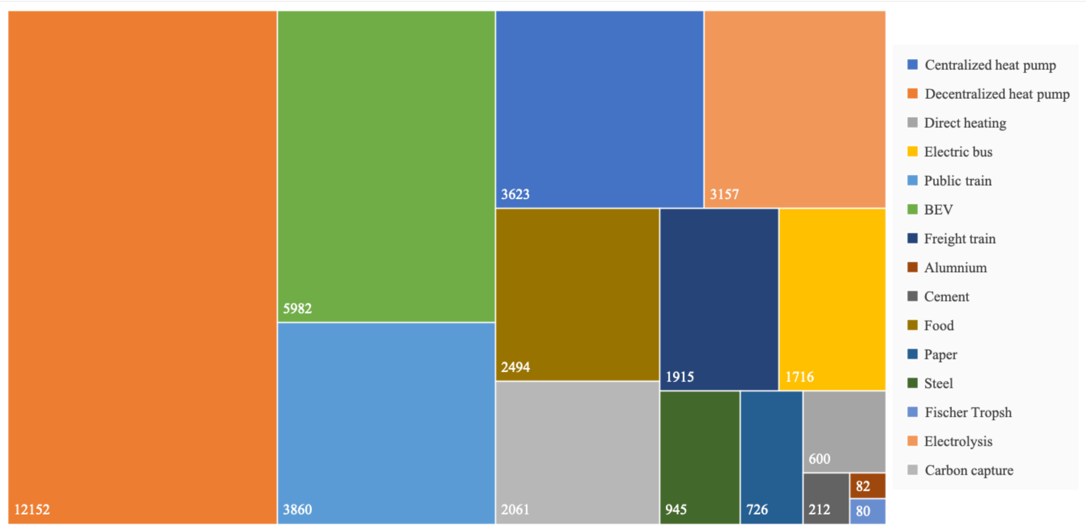


Figure 4.3: Electricity consumption [GWh/a] by technology

isfying the increasingly internal consumption by the energy system.

Therefore, in the blueprint of power supply, hydro and PV could be regarded as the most significant contributors from the authors' perspective. Considering the quasi-maturity of hydro power, PV with the greatest development potential, should be prioritized in strategy design for Switzerland. Heat pump and electric vehicles are promising to be major power sinks in 2050.

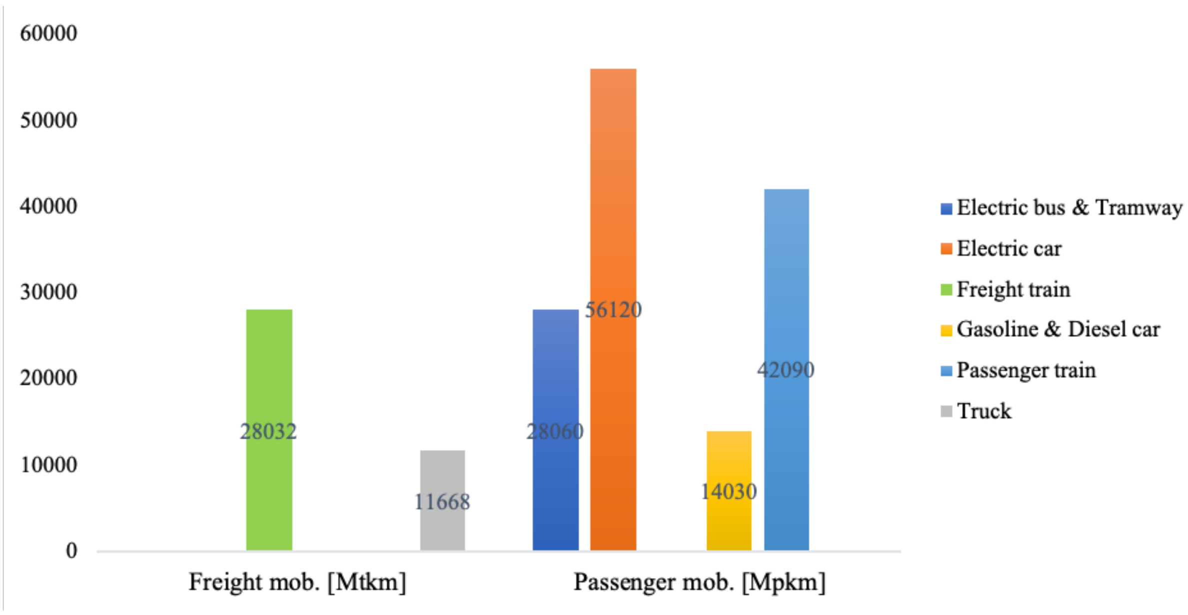


Figure 4.4: Optimization results on mobility mix

Mobility

Fig.4.4 depicts the utilization of vehicles in the energy system, where public transportation reaches its given limit accounting for 50% in passenger mobility. As presented in the previous paragraph, electric vehicles are expected to boom in the mobility mix, covering private cars and public transportation. Additionally, fuel-based vehicles are all fed by renewable sources, which will be discussed later.

Storage

With respect to the short-term storage, 3.7 GW battery is required from the modeling results in order to manage the daily variation.
The seasonality of long terms storage is presented in Figure 4.5: storage levels of all the considered chemicals and electricity climb upwards in summer, and peak in September; after which, a consecutive drop is observed down until the March next year reaching the trough. This trend appears logical and consistent to Switzerland's situation where energy deficit occurs in winter and surplus in summer, particularly with massive penetration of PV aforementioned. Among all storage methods, hydro power storage dominates due to its techno-economic maturity; hydrogen and natural gas storages become non-negligible with the highest level up to 2000 GWh. Additionally, bio-liquids and e-liquids call also for storage, despite their small scales, approx. 300 GWh. Summing all this up, the total long-term storage level amounts to 11000 GWh at maximal, which accounts for around 14% of the total annual power output.

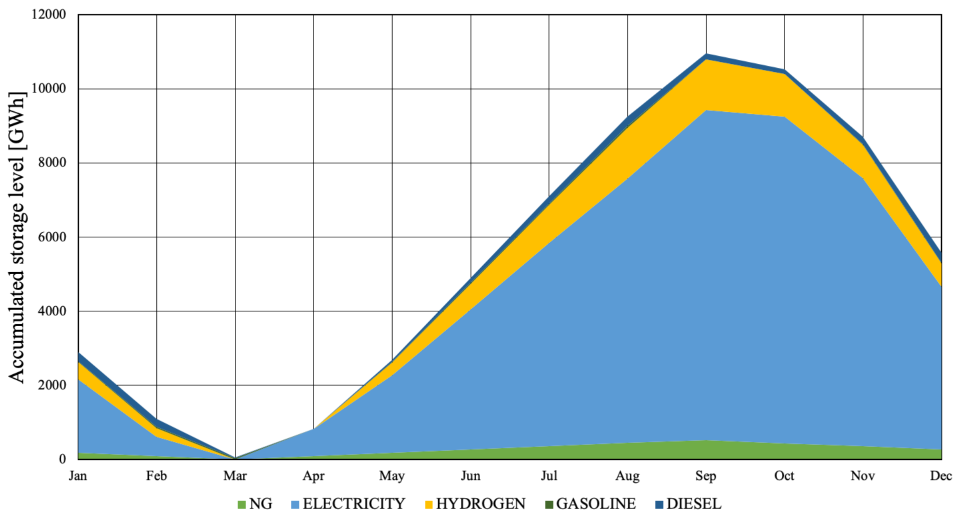


Figure 4.5: Modeling results of accumulated seasonal storage levels for natural gas, electricity (hydro power), hydrogen, diesel and gasoline.

4.1.2 Results of carbon flows

In parallel to the energy balance, carbon flows are also quantified and represented in Fig.4.6 in order to track the footprints and clarify how the -6 Mt CO2 emission is realized. As a result, all the carbon flows take place above-ground (except CCS), where biogenic and non-biogenic sources are identified and quantified.

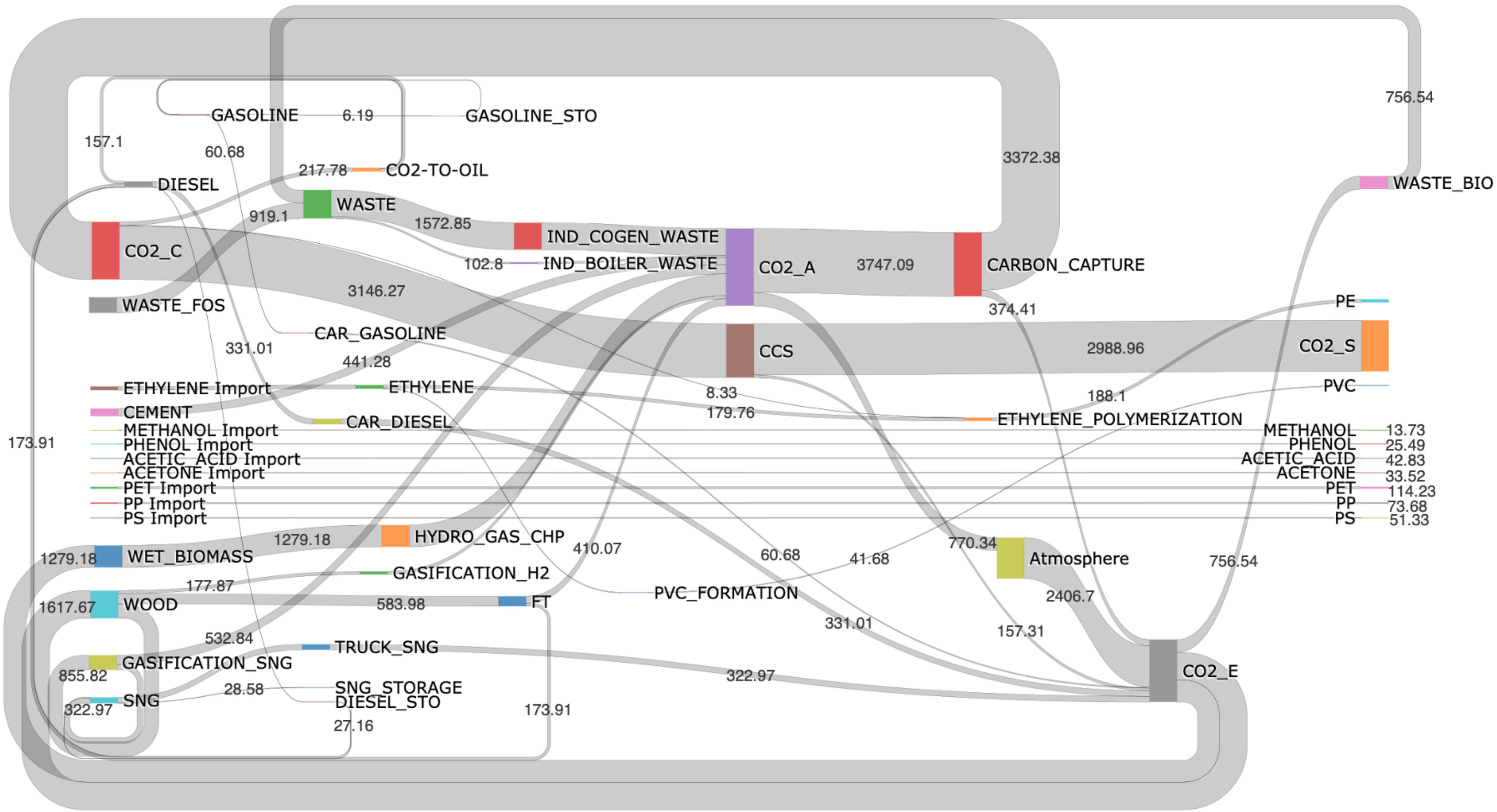


Figure 4.6: Quantitative representation of the carbon flows [kt-C/a] in Swiss energy systems

For biogenic sources, negative emissions are observed from the CO2 in the environment to biomass (wood, wet biomass and bio-waste), namely the flows CO2_E → biomass in the Sankey figure, representing the process of biomass formation. Carbon capture is largely applied to waste, cement, and bio-fuel production processes (decentralized technologies not included due to limited scale of deploying CC technologies, e.g. a car or a small boiler), part of fugitive emission going from CO2_A → Atmosphere, and the captured carbon is represented by CO2_C. On one hand, the majority of CO2_C is sequestrated underground via CCS process (CCS → CO2_S) with a small portion of fugitive emission to atmosphere (CCS → CO2_E), which is regarded not capturable anymore by conventional CC technologies except by biomass; on the other hand, the remaining captured CO2 participates into the process of ethylene polymerization, as well as liquid fuel generation (CO2_C → CO2-TO-OIL → GASOLINE & DIESEL). The synthetic fuel, take diesel as an example, is then consumed by diesel car which emits CO2 directly into the atmosphere (DIESEL → CAR_DIESEL → CO2_E): it forms an enclosed loop from CO2_E to CO2_E, tracking the whole pathways of biogenic carbon. Additionally, several processes named with "_STO" in this Sankey present the seasonal storage, such as the loop SNG → SNG_STO → SNG.

In the highly circular carbon system, wood is mainly used via gasification for SNG and hydrogen, as well as by the Fischer-Tropsh process for liquid fuel. From the results, gasification appears the most competitive for wood valorization. Almost all wet biomass is converted into SNG, among which 80% is burned in CHP for providing heat and power, the remaining 20% for mobility.

As the only imbalanced box in the Sankey, the Atmosphere denotes the negative emission by the difference of its inlet 770.34 kt-C and outlet 2406.7 kt-C, representing the biomass captures more carbon from the atmosphere than the system emits. By multiplying the molecular mass ratio of CO2 over C (44/12), this value corresponds well to -6 Mt CO2. Table 4.1 gives an overview of the carbon audit, showing 10.96 Mt-CO2 needs to be sequestrated annually.

Table 4.1: Carbon flow audit [kt-C/a]

	Woody biomass	Non-woody biomass	Bio waste	non-bio Waste	Cement	Total
Carbon input	1618	1279	757	919	441	5014
Carbon capture	1087.2	859.4	508.7	617.5	296.3	3372
Carbon sequestration	964.5	762.5	451.3	547.8	262.9	2989
Carbon utilization						
- Fuels	70.3	55.6	32.9	39.9	19.2	218
- Plastics	2.7	2.1	1.3	1.5	0.7	8.3
Net emission	-967.2	-764.6	-452.5	369.6	177.4	-1637

4.2 Uncertainty analyses

All the analyses presented in previous chapters are based upon a single scenario with a couple of assumptions that either the authors or the cited experts assume the most "plausible". However, uncertainty in the energy transition is non-negligible, which can even subvert investment and operational strategies based merely upon nominal results. Therefore, a single value for the concerning topics may not be enough, and as an improvement, we render an uncertainty range for each of the issues in interest in this chapter, which is supposed of having more practical implications in policymaking.

Uncertainty could be classified into two categories: endogenous and exogenous. For example, the import price is reckoned as exogenous in this model, while the installation sizes for technologies are regarded as endogenous. In order to facilitate the uncertainty test, a platform based upon R shiny is built allowing for running Sobol Sequence exploring the whole solution space in an equiprobable way, or Monte Carlos simulation by user-specific distributions. The steps for carrying out the uncertainty test are listed as follow:

- Identifying uncertain factors, defining their uncertain ranges (and distribution laws for Monte-Carlo simulation);
- Input the number of simulation;
- Obtain, visualize and analyze the results through programmable graphs.

In this report, we use parallel coordinates for presenting the results (Fig. 4.7 and 4.8), in which each vertical coordinate represents either an uncertain parameter as input or a range as output. Infeasible tests in optimization are filtered out in the parallel coordinates. As introduced in Section 3, the uncertainty tests in this study concern three aspects: uncertainty impact from the demand side, uncertainty impact from domestic technology potential, and uncertainty impact from energy importation.

4.2.1 Uncertainty impact from energy efficiency improvement in demand side

We apply normal distribution for the uncertainty in the renovation saving, DHN share in low temperature heat supply, industrial saving potential, oil-based vehicles share, public transportation share in passenger mobility and train share in freight mobility. The other parameters in SES keep their nominal values. For the normal distribution $\sim \mathcal{N}(\mu,\sigma)$, where the vector μ represents the arithmetic averages of the given min and max for all uncertain parameters, and the vector σ is estimated by $\frac{1}{6}(max - min)$ resulting in a $\pm 3\sigma$ confidence interval. In this study, 1000 Monte Carlo simulations were carried out, and the results are reflected in the Fig. 4.7. In the upper half of the figure lies the parallel coordinate containing all uncertain inputs and corresponding results; in the bottom half, the corresponding distributions of the results are represented by the bar chart, where the 5 vertical lines (some may overlap) in each horizontal box represent respectively the min, 1/4 quantile, median, 3/4 quantile and max in their respective ranges.

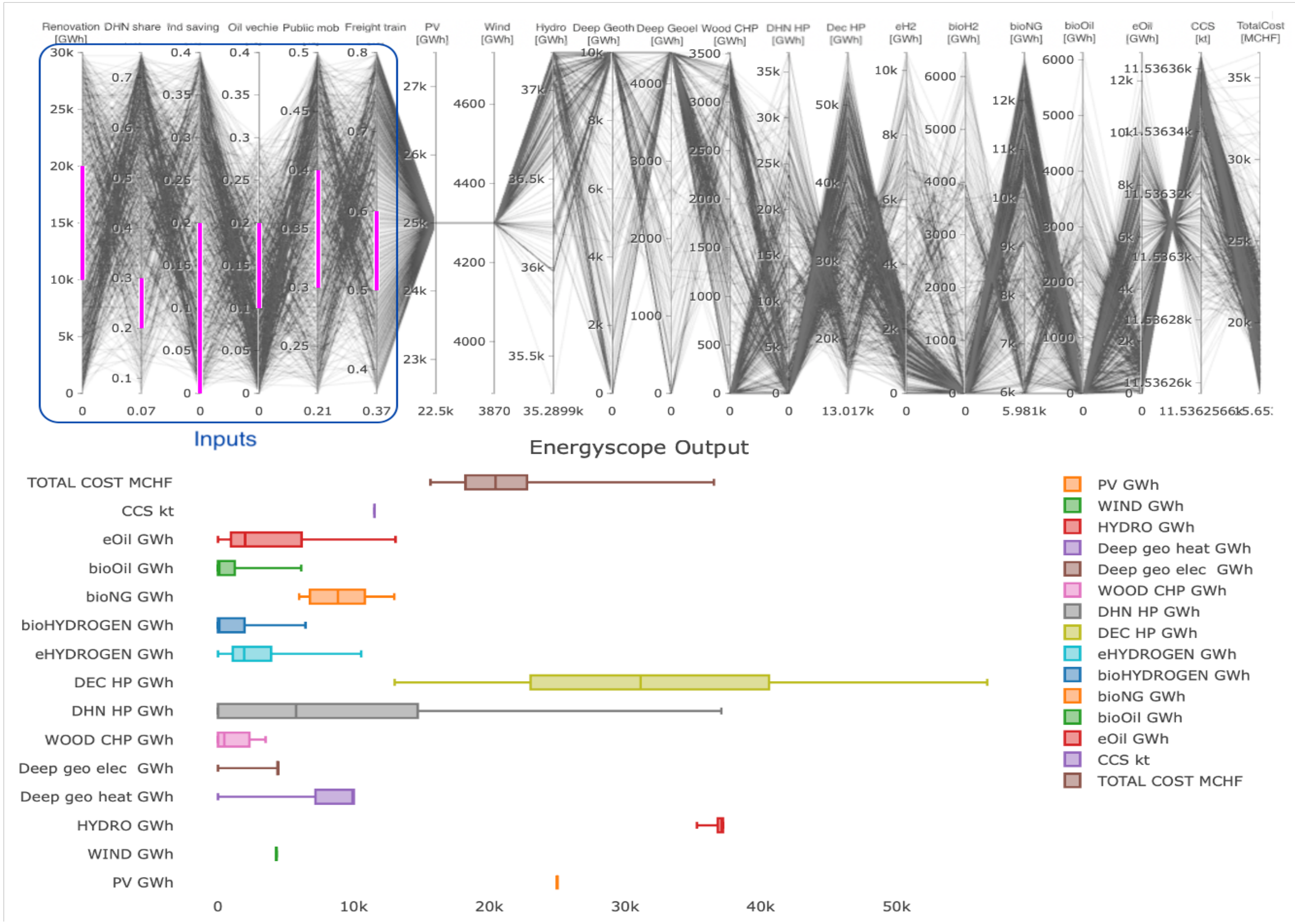


Figure 4.7: Uncertainty test result on the impact of energy efficiency on key areas in Swiss energy system.

From the box chart, large uncertainty ranges of DHN and DEC heat pumps are witnessed, which present reverse-correlation mainly decided by the DHN share. The production of biofuels and e-fuels varies in different situations, but commonly between 0-15 TWh. The total cost of the system shows a relatively large range between 15 - 40 bCHF/a. It should be highlighted that several technologies remain robust against demand uncertainty, such PV, wind, hydro and CCS: by consequence, they are supposed to be considered in priority in decision making.

4.2.2 Uncertainty from domestic technology potential

The above uncertain results are based upon the prerequisite that the installation capacity for technologies could reach their estimated limits. However, these limits themselves remain uncertain: any increase or decrease would probably lead to different investment and operational strategies, in particular for key technologies. In order to understand how the energy system reacts to different penetration of PV, wind, biomass, waste and geothermal, we take the uncertain inputs as shown in Fig. 4.8, assuming the demands are in their nominal values as reported in 4.1. In accordance to 4.2.1, 1000 Monte Carlo simulations with nominal distribution law were carried out, and the corresponding results are presented in the Fig.4.8.

Based on the tests, the variation of key technology outputs plays a significant role in the blueprint of energy fields. In the scenario where CCS amount is the lowest (see the small purple vertical line in the CCS coordinate, around 10 Mt/a), it is observed that the fossil waste remains always in the lowest level, which contributes the majority of non-biogenic carbon sources and is thus in priority to be removed; woody biomass is mainly used in bioNG and bioOil production, as well as in CHP, with very limited gasification for hydrogen, which is, instead, produced mainly by electrolysis, in line with a large penetration of PV (above 35 TWh). It reveals, to some extent, possible competition between e-hydrogen and bio-hydrogen production: from the further results reflected in Fig.4.9, bio-hydrogen is produced only when PV is less than 30 TWh, ranging between 0 - 5 TWh depending on specific system configurations. One possible explanation for this phenomenon is that the excessive electricity accompanied by increasing PV panels requires storage, and due to the saturation of hydro storage, electrolysis takes place as an effective power sink for producing storable hydrogen which could be converted to other fuels as well. In this situation where hydrogen is produced already in a relatively large scale, the utilization of wood focuses on producing heat and power in CHP, or synthesizing other types of fuels, such as SNG or diesel.

In resume, biofuels and efuels production vary in different scenarios, but are all limited within up to 15 TWh ranges; centralized heat pumping seems less competitive to the direct usage of deep geothermal heat, displaying a large uncertainty range, while the decentralized heat pumping appears quite stable and in large demand. In addition, the amount of CO2 that needs to be sequestrated each year remains steady (10-15 Mt) regardless of the variation of technology mix in the system.

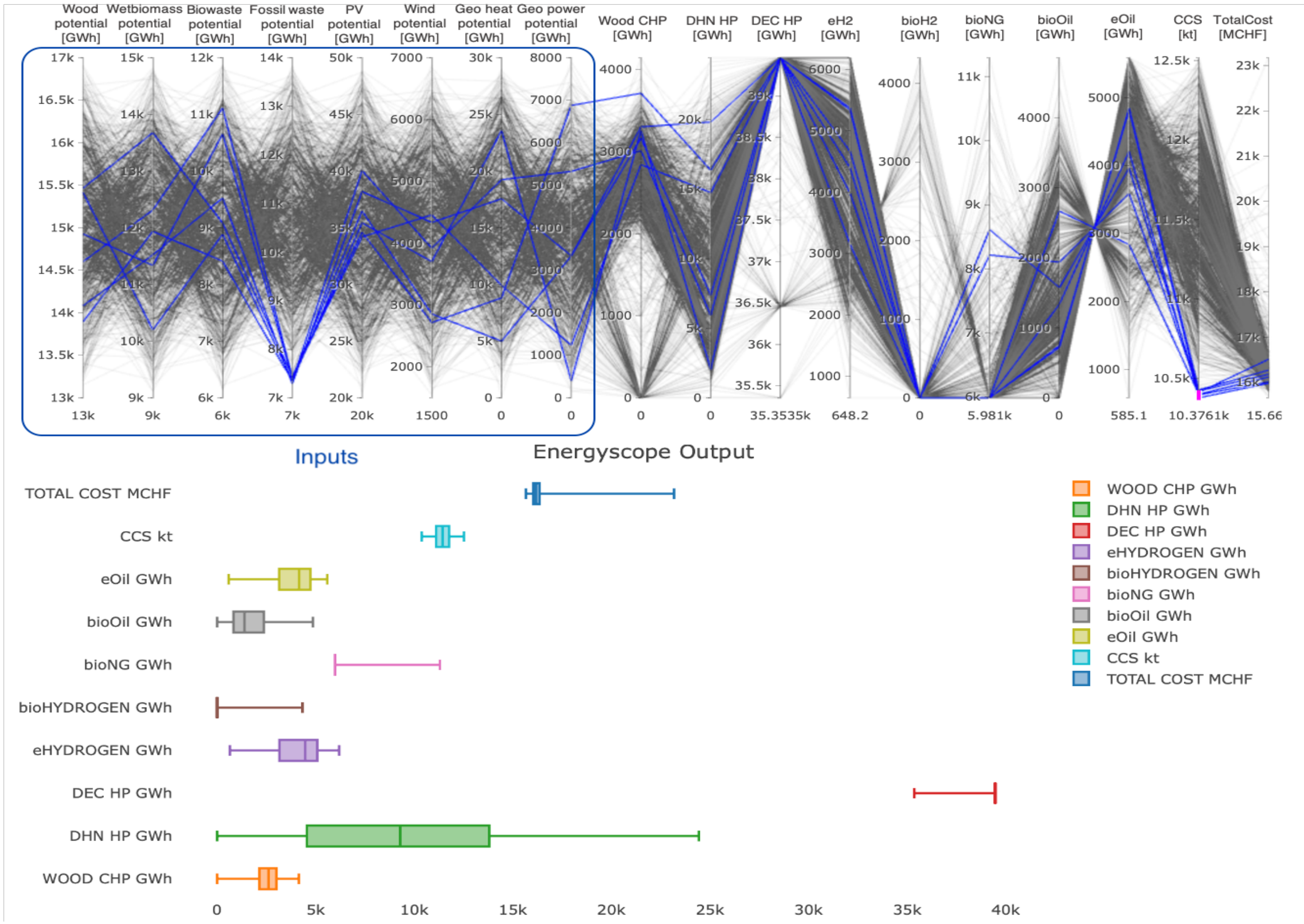


Figure 4.8: Uncertainty test result on the impact of availability of domestic resources for Swiss energy system.

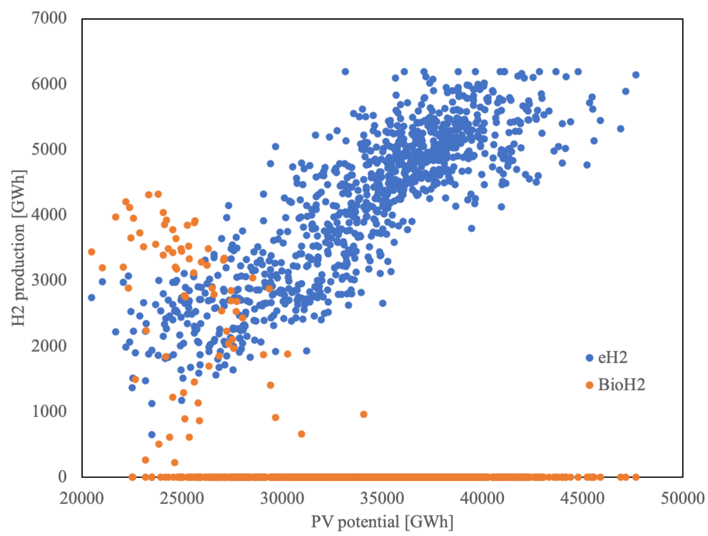


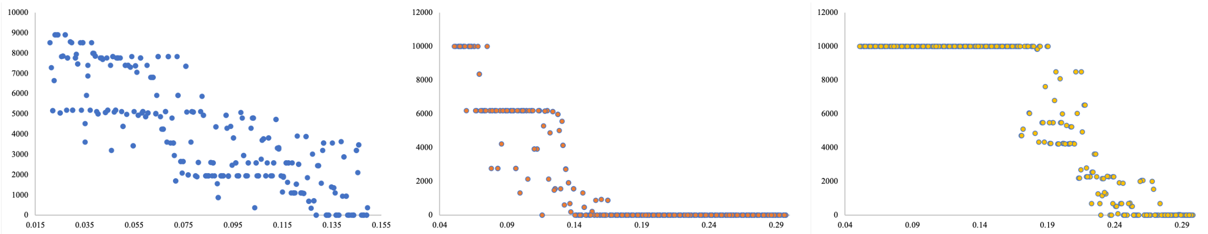
Figure 4.9: Uncertainty test results on hydrogen production with respect to PV penetration.

4.2.3 Uncertainty impact from energy importation

Having analyzed the realization of decarbonization based upon only domestic resources, this section discusses the impact of energy import on the system.

Import relates to a couple of issues: firstly, import what? excluding fossil based resources, electricity, SNG and hydrogen are reckoned as the major import resources. Secondly, from where? This question is not clear since in 2050 biomass and hydrogen are supposed to be in massive demand in other countries, especially in the EU, in order to meet the COP21 objectives, implying there is a large possibility of an absence of available clean resources for import. According to GrosseRuse (2018), complete decarbonization of the energy sector, the EU would have to reduce its gas consumption by 80%. Only then some of the renewable gas potentials would be disposable for Switzerland. Since the existing networks allow long distance transportation and distribution of natural gas at low energy penalty, biogas import from remote markets rich in low-cost biomass, such as Russia, Ukraine, is also feasible theoretically. However, the technical potential for biomass in Russia is estimated to be 431 TWh/a, of which 285 TWh/a is economically feasible (Douraeva, 2003, Karjalainen and Gerasimov, 2008). This value is approximately as 10 times as the Swiss domestic biomass stock, which seems quite limited knowing Russia's huge energy demand and its strategy to maximize the use of domestic energy sources. Concerning power import, it is even more uncertain due to the increasing intermittency of the massive penetration of PV and wind in EU countries. By consequence, the importable quantities of foreign renewable resources for Switzerland in long terms are completely unclear.

Nevertheless, importation could still be an option in decision-making if it is economically competitive. The third question comes up how much to import if the resources are available? In order to explore the impact of importing price on the importing quantity, we apply Sobel sequence on the import price for electricity, hydrogen and SNG (biogas). The reason of Sobel sequence instead of associating a distribution law results from the lack of valid methods predicting the high volatility of energy prices in the future, and therefore a necessity to explore the whole solution space in a non-biased way. The



(a) Electricity (b) Hydrogen (c) SNG

Figure 4.10: Impact of resource prices (horizontal axis: CHF/kWh) on annual import amount (vertical axis: GWh/a).

ceiling of electricity import is set by referring to today's level 30 TWh/a, while hydrogen and SNG are assumed to be at maximal 10 TWh/a. The results illustrated in the Fig. 4.10 shows that electricity import is preferential which facilitates the flexibility of the system, even if in some cases with relatively high import prices (>0.1 CHF/kWh). The maximal optimal electricity import is around 9 TWh/a over all uncertainty tests, and only occurs in winter. Hydrogen is not supposed to be largely imported unless its price drops to below 0.14 CHF/kWh. From the results, SNG shows its robustness against price uncertainty with a relatively high cut-off price, probably due to its convenience in utilization and relatively low costs for investment.

4.2.4 Model limitations

As a "snapshot" model, SES depicts the optimal energy system blueprint in 2050 and displays competitiveness in uncertainty analysis; however, it is not able to generate developing pathways. In terms of the modeling approach, this study is based upon optimization method striving for cost minimization, which does not necessarily imply profit maximization. Increasing non-dispatchable energy sources may lead to the intensification of price arbitrage by shifting purchase-selling timing in the future. Nevertheless, we suppose a cost-based model is fundamental in strategy making by checking the potential limits that the Swiss energy system could afford in order to realize decarbonization, and based upon which, further research could be developed exploring valorization possibilities.

As mentioned, as a long-term prospective model, it is difficult to account for short terms variations, e.g. the stability of frequency and voltage for power grids which demand for seconds or even milliseconds' granularity. Energy models on micro-temporal scales are necessary for refining the operational strategies. In addition, the development of the energy system calls for infrastructure support, which was not modelled in a detailed way.

Chapter 5

Conclusion

In the sense that "all models are wrong" (George Box, 1976), it is impossible to predict perfectly the configuration of Swiss energy systems in long terms due to its complexity and stochastic factors, such as interest rate or black swan events, etc; however, plausible projections associated to uncertain ranges for different scenarios allow for a general view on the possible solutions in the future. Despite a bunch of scenarios towards decarbonization where strategies may vary, a couple of commonalities are observed from the modeling results, and some conclusions could be drawn:

- Energy autonomy and carbon neutrality could be realized in 2050, in the condition of a quasi 100% renewable-based supply system structure with CCUS as well as adequate infrastructure support.
- Energy efficiency plays an essential role in the energy transition. According to the data reported, direct effect by saving from the energy demand side can be as important as developing new capacities. Building renovation, innovative process design in the industry, and electrification of mobility are paramount for achieving this goal.
- From the supply side, the most promising technologies that are supposed to develop on large scale are PV for power, biomass for green fuels, and geothermal with HP for heating: the former two are observed to reach their potential limits in almost all scenarios. PV potential determines to a large extent the Swiss energy system typology in the future, due to its relatively large potential and strong reverse seasonality with respect to supply-demand. Controversy exists for deep geothermal utilization as a result of the unknown underground structure and possible impact on rock, soil, and water. Further study and more pioneering projects are necessary to demonstrate its geological-ecological feasibility. Shallow geothermal with heat pumps appears less risky and is promising to serve as the pillar for building heating supply in the future. Cost reduction on the heat pump installation would accelerate significantly the decarbonization process.
- Hydrogen is expected to be a vital intermediate energy carrier facilitating sectors' coupling. Electrolysis and biomass gasification contribute considerably to hydrogen production. The role of electrolysis is supposed to get reinforced with increasing PV penetration.
- Seasonal storage would play a non-negligible role in energy supply in order to accommo-

date the development of renewables. Hydro storage is supposed to continue to dominate, while the natural gas storage and hydrogen storage serve as major backups, contributing to increasing flexibility for the system.

- Without a large scale of CCS (~10 million tons per year), it seems impossible to achieve carbon neutralization for Switzerland in 2050. Biomass-based plants, waste incineration, and cement industry are the key areas for the deployment of carbon capture technologies. CO2 network is supposed to be planned from now on in the authors' opinion.

One important message Covid-19 conveys is that possible black swan events may change international circumstances, highlighting the necessity of autonomy in certain areas facing unexpected crises. In the authors' view, the resilience of the energy system seems more vulnerable than conventional manufacturing industries, due to lack of fossil resources in Switzerland and difficulty of electricity storage. In this perspective, over-reliance on resource import, even including possible biogenic resources import for the decarbonization purpose, is likely to subdue the robustness of the Swiss energy system against possibly unpredictable crises. Therefore, this report inclines to prioritize the utilization of domestic resources towards decarbonization in 2050 over importation, despite the flexibility the latter may bring about for the energy system.

In conclusion, a radical revolution of the current energy system is required in order to realize the decarbonization objective in 2050. Despite the developing strategies demonstrated by the modeling results in this study, it requires industrial pilot projects for further demonstration and benchmarking, in particular the development of biomass and CCUS technologies as well as auxiliary infrastructures.

Appendix A

Data

The Appendix lists some of the data used in this study. For more information, please see the previous reports Moret (2017), Stadler et al. (2019) and the database JASM (2020).

Fig. A.1 shows the principal chemicals and plastics demand in 2017 for Switzerland.

A.1 Chemical and plastics demand

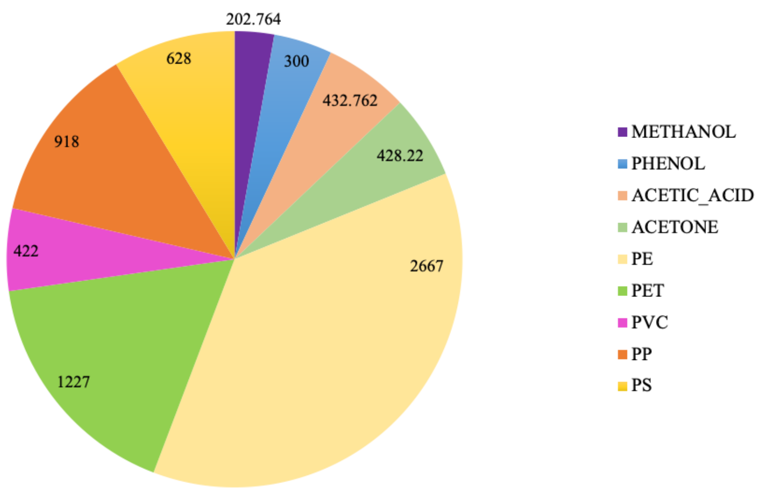


Figure A.1: Chemical and plastic demands in 2017 Switzerland [GWh], adapted from Stadler et al. (2019)

A.2 Carbon capture in energy sectors

Table A.1: Key parameters for carbon capture technologies in major energy sectors

Sector	Subsector	TRL	Capture efficiency [%]	Steam consumption [kWh/tCO2]	Electricity consumption [kWh/tCO2]	Cost[2] [CHF/tCO2]	Source	Comment
Power plant[3]	NGCC	9	80-93	694-1055	0[4]	92-138	(Jenni et al., 2013), (Jansen et al., 2015), (Rubin et al., 2015),(Irlam, 2017)	20% - 40% energy penalty
	Wood Combustion	9	90	920	0	88	(Pröll and Zerobin, 2019), (Consoli, 2019)	36% energy penalty
	Waste incineration	-	90	458	0	32-46	(Wienchol et al., 2020), (Kearns, 2019)	Post combustion: CO2 capture for a waste to energy plant is simpler than for a coal-fired power station (less sulphur and particulates). 14.7% energy penalty
SNG	Wood gasification	9	90	236	0	25-27	(Dinca et al., 2018)	Overall efficiency was reduced by 5.1% and 3.9% respectively without and with heat recovery.
Steel	BF-BOF (air blown / top-gas recycling)	7	-	694-1222	125-150	30-65	(Kuramochi et al., 2012)	Chemical absoption MEA
	scrap-EAF	-	99	0	0		(CCS Institute, 2017)	The EAF process requires large amounts of electricity to melt the scrap steel but has no other sources of CO2 emissions: no need for carbon capture

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Table A.1 – *Continued from previous page*

	Hisarna	-	95	0	0		(Kuramochi et al., 2012)	In this setup, the input carbon is fully oxidized within the smelter so that CO2 removal is unnecessary
	DRI-EAF	7		0	94		(Gielen, 2003)	
Cement	dry/wet-kiln, geopolymers	6	60	0	203	25-68	(Kuramochi et al., 2012)	Oxyfuel in pre-calciner
	dry/wet-kiln, geopolymers	6	94	0	275		(Kuramochi et al., 2012)	Oxyfuel entire plant
	dry/wet-kiln, geopolymers	7	80-94	750-1028	150-203		(Kuramochi et al., 2012)	Chemical absorption (MEA, etc.)
	dry/wet-kiln, geopolymers	3	61	0	150		(Kuramochi et al., 2012)	Calcium looping
Chemicals	Methanol, DME, FT fuels production	9	95	611-659	12-13	30-46	(Meerman et al., 2012)	Water-gas shift reaction, pre-combustion, chemical absorption (MDE)
	Methanol, DME, FT fuels production	9	90.5	0	123		(Riboldi et al., 2014),(Ho et al., 2008)	Water-gas shift reaction, pre-combustion, physical absoption
	Methanol, DME, FT fuels production	6	85.4	0	144		(Riboldi et al., 2014),(Ho et al., 2008)	Water-gas shift reaction, pre-combustion, PSA with flash seperation
	Methanol, DME, FT fuels production	6	90	0	94		(Susarla et al., 2015)	Water-gas shift reaction, pre-combustion, PSA
	Ethanol	-	100	0	0		(Kheshgi and Prince, 2005)	The fermentation process releases almost pure CO2 which does not require specific separation equipment
Paper/Wood pulp	black-liquor burner	7	62	1163	0	25-40	(McGrail et al., 2012), (Consoli, 2019), (Leeson et al., 2017)	Chemical absorption (MEA)

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Table A.1 – *Continued from previous page*

	black-liquor gasification	3	88	0	1468		(Ferreira and Balestieri, 2015)	Pre-combustion
Direct air capture	HT	3	-	1535	0	388	(Fasihi et al., 2019), (Viebahn et al., 2019)	High temperature aqueous solution
	LT	3	-	250	1750	244		Low temperature solid sorbent

[2] All the costs are converted to 2015 value based upon CEPCI index. Large variation on the cost in different literature.

[3] Only natural gas power plant considered, since its relative large scale in Switzerland. No coal power plant exists in Switzerland today, nor will in the horizon 2050 according to SFOE (2018); no available industrial data for carbon capture in oil power plants.

[4] Electricity consumption included in steam consumption by self-production & consumption hypothesis.

A.3 Resource import

The Table A.2 summarizes the current import of natural gas and hydrogen from abroad.

The Table A.3 summarizes the current import of natural gas and hydrogen from abroad.

Table A.2: Monthly import amount and price of natural gas and hydrogen in 2019, based upon Swiss-impex (2020)

	Import [kg]		Price [CHF/kWh]	
	NG[a]	Hydrogen	NG[a]	Hydrogen
Jan	367562170	7934	0.03488697	0.219676078
Feb	372895450	8330	0.032362442	0.190915966
Mar	365058331	11783	0.031896005	0.17579394
Apr	235143226	12311	0.032183894	0.185300138
May	253417848	13577	0.029468676	0.174292554
Jun	169251171	12704	0.029255645	0.185639169
Jul	109093811	15299	0.028170895	0.132883195
Aug	84227021	8840	0.037442447	0.173188914
Sep	84357656	11942	0.047976939	0.351689834
Oct	113522024	12606	0.059719833	0.187727273
Nov	192925684	8044	0.026319939	0.135126803
Dec	303794140	6637	0.023266905	0.1910336

[a] NG in liquid state (LNG) not included.

A.4 Technologies summary in Energyscope

Fig.A.2 gives an overview of the major technologies modeled in SES.

Table A.3: Cross-boundary power import quantity, gwp, price from neighbouring countries to Switzerland in 2019, based upon Kantor and Santecchia (2019), SwissGrid (2020)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Quantity [MW]												
AT	834.46	999.59	969.55	474.34	351.02	475.67	176.55	93.00	279.09	394.39	618.63	334.73
DE	3162.54	3117.71	2367.96	1121.69	404.58	161.43	81.20	80.39	1124.65	1936.63	2233.42	2226.14
FR	278.16	955.49	1096.81	491.75	1311.24	1022.44	538.81	635.17	1182.26	1184.06	648.65	1248.27
IT	8.47	0.00	8.02	59.93	22.65	7.92	0.00	7.16	0.13	0.00	3.24	46.37
GWP [gCO2eq/kWh]												
AT	357.48	358.96	249.38	217.18	161.36	141.01	243.30	234.53	294.20	346.04	312.30	328.43
DE	483.23	488.59	359.00	424.32	426.26	375.41	416.75	413.69	395.56	391.12	508.77	370.94
FR	109.64	90.93	66.45	56.32	49.88	48.92	71.69	60.38	76.93	75.41	120.92	85.54
IT	445.58	403.36	390.05	395.64	343.51	338.15	369.38	379.52	406.99	413.54	380.07	360.43
Price [EUR/MWh]												
AT	56.01	46.04	33.24	37.73	37.93	34.60	40.05	37.71	38.04	37.87	42.74	38.11
DE	49.39	42.83	30.72	36.96	37.84	32.52	39.69	36.85	35.75	35.82	41.00	31.97
FR	61.16	46.62	34.11	38.05	37.21	29.26	37.64	33.39	35.54	37.25	45.94	36.46
IT	67.61	57.29	53.73	53.32	49.68	44.81	50.65	45.23	50.69	52.70	48.06	42.28
Resume												
Total import [MW]	4283.64	5072.79	4442.34	2147.71	2089.50	1667.46	796.56	815.72	2586.13	3515.08	3503.93	3855.51
Avg. GWP [gCO2eq/kWh]	434.40	388.15	262.90	293.51	144.67	108.17	144.90	117.86	238.96	279.71	402.17	274.72
Avg. Price [EUR/MWh]	51.48	44.18	32.15	37.83	37.59	31.17	38.38	34.33	35.90	36.53	42.23	34.08

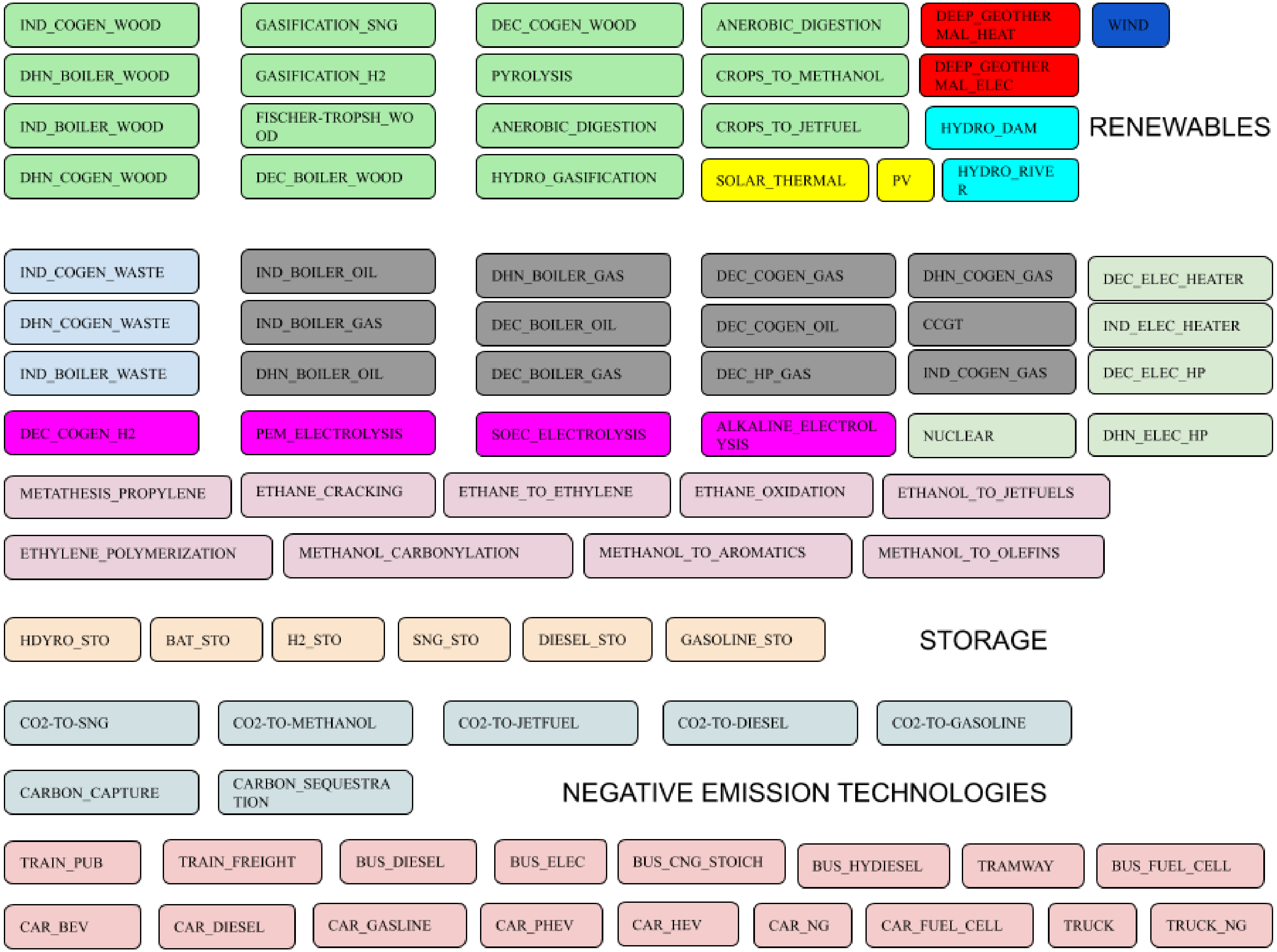

Figure A.2: Technology overview in SES.

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