Joint Activity Scenarios and Modelling

Probabilistic assessment of the Swiss energy strategy - Scenario analysis with the SES-ETH model

Adriana Marcucci
Gianfranco Guidati
Domenico Giardini

ETH Zurich

January 22, 2021

Supported by:

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Innosuisse – Swiss Innovation Agency

Contents

Chapter 1

Call for action

We analyzed different technical options for Switzerland to reduce its greenhouse gas emissions to net-zero by 2060, considering the uncertainty of major drivers such as population growth, climate or technology characteristics. We can formulate the following stable conclusions and recommendations:

- To reach the Swiss net-zero greenhouse gas (GHG) emissions target, the energy sector (electricity, heat, mobility, including emissions from calcination in cement plants) will need to reduce its CO_2 emission from 38.3 Mt_{CO_2}/a in 2015 to **negative levels of -4 to -8 Mt_{CO_2}/a** in 2060. This assumes 4–8 $Mt_{CO_2}/a$of unavoidable carbon emissions from agriculture, non-energy emissions from waste, and others.

- The net-zero target can only be achieved by capturing and storing CO_2 from the existing 6 cement and 30 municipal waste incineration plants, from possible gas turbine combined cycles, and from wood gasification and natural gas reforming plants, that deliver hydrogen and CO_2. Since part of the primary energy entering these plants is biogenic in nature, this approach allows for **negative emissions that can compensate the unavoidable emissions**.

- The total amount of stored CO_2 will be around 15–20 Mt_{CO_2}/a (around 1.5–2 t CO_2 per capita). Since current studies show that Switzerland does not have sufficient domestic storage capacity, the country should **actively contribute to the growth of a European CO_2 transport and storage infrastructure.**

- Extrapolating these 1.5-2 ton per capita to the European Union with approx. 500 mio people, results in a need for storing up to one Gigaton of CO_2 per year. Estimates for the storage potential in Europe amount to more than 100 Gt CO_2 (IOGP – International association of oil & gas producers, 2019). Assuming a stable operation after 2050/60, it is clear that **a GHG reduction strategy based on carbon capture and sequestration (CCS) has a time span of a century, making it worthwhile to invest in the necessary infrastructure.**

- Hydrogen plays a dual role in the future Swiss energy system. It allows to decarbonize those parts of road transport that cannot be easily electrified (e.g. heavy duty freight transport), and it can supply high temperature process heat to industry. At the same time, it can generate negative emissions during production, whenever the primary energy input is biogenic in nature. This is the case for wood gasification and biogas reforming, both coupled with CCS. **Technol-**

ogy development in this field must be accelerated in close collaboration with private and public partners that act as hydrogen customers.

- Deep geothermal energy can contribute with baseload CO_2 free thermal energy. **It should be developed and applied primarily to district heating, low temperature industrial processes and new processes such as the desorption step in CO_2 separation.**

- Solar thermal collectors are a valuable addition to a net-zero technology mix because they allow to save limited resource (e.g. wood or methane). Solar thermal can be used in single and multi-family houses, district heating schemes, industrial processes and CO_2 separation, usually coupled with a short-term or a seasonal thermal energy storage. Solar collectors should also be used to regenerate borehole fields of ground source heat pumps.

- Industrial process heat will have to completely abandon the use of fossil oil and gas. For medium temperatures, **geothermal and solar thermal** is an interesting option to be explored. Whenever the source temperature does not reach the level required for the process, **high temperature heat pumps should be used.**

- High temperature process heat can be generated using hydrogen or waste. Industrial waste incineration plants should be co-located with heat customers. Direct electrical heating is an interesting option that can exploit the strong photovoltaic generation in summer. It has to be coupled some sort of storage, either a short-term storage (hours to days) or even better with a seasonal storage. Applied research and demonstration in this field should be undertaken with industrial partners.

- Large scale seasonal thermal energy storage helps to seasonally balance the energy system. Heat can be collected in summer with solar collectors, large scale heat pumps and industrial electric heaters that use excess photovoltaic generation. This has a positive effect that goes beyond the heating sector because it allows for a lower electricity consumption for heat pumps in winter. **Despite the issue of expensive land in Switzerland, well-developed seasonal storage options like open-pit storage should be demonstrated with private and public partners.**

- **Photovoltaic generation will have to grow by a factor of 10 compared to the levels of 2020.** We find, that PV will generate 20–30 TWh/a in 2060, which corresponds to the quantity supplied today by nuclear power. However, these two technologies cannot be compared. While nuclear delivers reliable baseload generation, photovoltaics exhibits fluctuations on all scales from hours to days and seasons.

- Integrating solar photovoltaics requires the interaction with many parts of the energy system. First, storage hydropower is forced into a diurnal on-off operation – and must avoid negative effects on the aquatic ecosystems. Second, pumped hydro storage and batteries are used to shift electricity from day to night. Finally, various types of conversion technologies (heat pumps, electric heaters, electrolysis) allow for sector coupling, i.e. they use the residual excess generation from photovoltaics and make it available in the other energy sectors, often with the help of short to long-term storage. Our results indicate that this is possible from the point of view of hourly energy balances – however, this poses important challenges for the control of the system.

- Given the importance of photovoltaics, its integration into new buildings should be mandatory. However, this requires additional steps. Buildings are designed by architects and they need technically feasible and aesthetically pleasing options, that go far beyond a PV panel that is retrofitted onto a roof. **The optimal integration of photovoltaics into the building envelop should become part of the university curriculum.**

- The electrification of the demand sectors heating and mobility is a crucial step in any decarbonization scenario. As a consequence, electricity consumption will increase to 70–90 TWh/a. Investments in energy efficiency, both in the residential and industrial sectors are generally cost-effective. **Incentives and regulations that foster this development should be put in place.**

- Wood is an important source of renewable energy and of biogenic CO_2. Its potential is not fully exploited by burning it for the purpose of residential heating, instead, it should be used to generate negative emissions, i.e. to extract CO_2 from the atmosphere and to store in in the subsurface. **This can be achieved by wood gasification to hydrogen or by wood power plants equipped with CO_2 separation.**

Chapter 2

Taking decisions under uncertainty

The aim of this work is not to precisely predict or even design an energy system of the future. Our objective is to identify technologies that are very likely part of the future mix, those that are uncertain because they depend on drivers that cannot be controlled, and the ones that will unlikely play a role. To achieve this goal, we develop a probabilistic assessment of the Swiss Energy Strategy, in which we consider the uncertainty of macroeconomic drivers, climate change, technology development, market integration and climate change policy.

Most drivers that influence the future energy system are uncertain. In our analysis we consider two categories of uncertainty and treat them differently. The first category relates to levers on which citizens and policymakers can exert influence to reduce greenhouse gas emissions, including: climate policy, availability of technologies, and integration with the EU energy system. We use these drivers to define the dimensions of a few *discrete* scenario variants. The second type of uncertainty includes those external factors that are not sensitive to domestic policies or individual behavior changes, including macro-economic drivers such as population and GDP; global climate change; technology costs; and cost and availability of resources. We analyze these uncertain factors with *continuous* probability distributions using a Monte Carlo simulation.

With this approach we obtain probability distributions for all resulting characteristics of the energy system, e.g. the amount of photovoltaic electricity generation or the use of wood in domestic heating. These results will reveal trends and inter-dependencies which are more informative than point-estimates alone: In comparing the set of results, we can identify the developments in the energy system that are more or less fixed – that are common to all the scenario results – and those that vary significantly. These types of insights are essential to inform decision making as we strive to meet net-zero emissions, since they allow us to formulate **robust recommendations for actions in the fields of research & development, pilot & demonstration and policy measures**.

All results are based on the Swiss Energyscope - ETH (SES-ETH) model (Marcucci et al., 2021a) that was developed at ETH based on original SES model (Moret, 2017). Several improvements have been introduced, most notably a tyoical day approach with hourly resolution. SES-ETH models the energy system, including electricity, heat and mobility. It solves a linear optimization problem that minimizes the total system costs by sizing all assets in the energy system, and by optimally dispatching all energy flows throughout a year. SES-ETH is a snapshot model that “jumps” into any selected year neglecting the evolution in between. The target year considered in this report is 2060.

2.1 Scenario definition

The SES-ETH scenarios are defined along three policy dimensions: climate policy, technology development and acceptance, and market integration. They are based on the overarching scenarios of the Joint Activity Scenarios and Modelling Marcucci et al. (2021b). In this section we describe in detail each dimension and the way we model it in SES-ETH.

2.1.1 First dimension: climate policy

In our scenarios, we aim at reaching net-zero GHG emissions in the whole economy ("CLI" in the JASM scenarios (Marcucci et al., 2021b)). However, the exact target for the energy system depends on reductions in other sectors, compensation abroad and the willingness of society follow this decarbonization path. The total GHG emissions in Switzerland in 2015 was 48.4 $MtCO_2$ equivalent (excluding international aviation and LULUCF). The total CO_2 emissions from the energy system (electricity, heat, transport) were 36.6 $MtCO_2$. The rest of the emissions correspond mainly to agriculture with 6 $MtCO_2$ and the calcination reaction in cement plants with 1.7 $MtCO_2$.

The Federal Council (2019) estimates non-energy emissions by 2050 to be 2 Mt_{CO_2} for cement production and 4.8 Mt_{CO_2} for agriculture/food production. Swiss targets explicitly mention compensations abroad, however, it is not clear to which extent this will be possible in a future where most countries follow a similar decarbonization pathway. **Therefore, we consider that the net-zero GHG emissions target for Switzerland will require negative emissions from -4 to -8 Mt_{CO_2}/a within the energy system.** To analyze how the structure of the future energy system changes with the CO_2 target, we make a sweep from +20 Mt_{CO_2}/a to the lowest level that can be achieved for each scenario variant.

2.1.2 Second dimension: Available technologies

In the technology dimension, we assume different states of technology availability due to both technology development and the willingness of society and industry to adopt novel technologies. We consider two extremes, a conservative and a progressive technology development. In the conservative technology development scheme, we assume a set of available technologies in line with current learning curves. While in this scenario expansion of existing technologies compared to current levels is possible, no significant changes into the existing infrastructure or expanded public acceptance are realized. The progressive option assumes accelerated learning and technology developments, increased social acceptance, and greater infrastructure investments such that there are more technologies available[1] in Switzerland at competitive prices.

The differences regard the growth of hydropower and wind power, the development of wood as an energy source[2], the exploitation of deep geothermal energy, and the availability of high temperature seasonal thermal energy storage in industry (see Table 2.2b). We do not consider the deployment of photovoltaics, solar thermal collectors or even district-scale seasonal thermal energy storage in this spectrum of conservative vs. progressive, since all these technologies are state-of-the-art (Table 2.1).

[1] More technologies available does not imply that these technologies will be chosen by the energy-system models.

[2] Scenarios for forest wood are based on Thees et al. (2018). They analyzed different scenarios for stock management, utilization, and cost limits. Our low potential corresponds to Moderate stock reduction + Less energy friendly use + Cost limit of 5.9 Rp/kWh. The high potential corresponds to Moderate stock reduction + Less energy friendly use + No cost limit.

Table 2.1: Available technologies

	Conservative	Progressive
Renewables potential		
Solar PV	50 TWh/a	50 TWh/a
Wind	1.7 TWh/a	4.3 TWh/a
Hydropower - inflow to dams	17.6 TWh/a	19.5 TWh/a
Hydropower - inflow to run of river	15.9 TWh/a	17.6 TWh/a
Geothermal heat	-	10 TWh/a
Forest Wood	7.2 TWh/a	10.9 TWh/a
Biomass pathways		
Gasification → Methanation → Biomethane	x	x
Gasification → Water gas shift → Hydrogen	x	x
Gasification → GTCC → Electricity/Heat	x	x
Anaerobic digestion (rural) → Gas motor → Electricity/Heat	x	x
Anaerobic digestion → Methanation → Biomethane	x	x
Vehicles		
Internal combustion (liquid, methane)	x	x
Electric	x	x
Hydrogen	x	x
Heating		
Boilers	x	x
Heat pumps	x	x
Electric heaters	x	x
Storage		
Storage lake capacity	6.5 TWh	8.4 TWh
Batteries	x	x
Gas storage (somewhere in EU)	x	x
H_2 seasonal storage	x	x
Seasonal low temperature heat storage	x	x
Seasonal high temperature heat storage	-	x

We neither explicitly model social acceptance and behavioral aspects of technology adoption nor competing market options (e.g., different electric car models) in SES-ETH. Instead, we assume that these technologies will be adopted once they become economically viable – it is the influence of the technology itself rather than individual products that we are interested in.

For both technology availability levels, we consider Switzerland a price taker. While the prices of technologies are the main driver for adoption in our models, the adoption rate or penetration does not influence the international technology price itself. Hence, the prices for technologies such as solar panels, boilers, heat pumps, vehicles, etc. are independent from both the scenario variants and the rate of technology adoption.

2.1.3 Third dimension: Market integration

Finally, we consider the degree of integration with the European energy markets concerning mainly the imports of energy carriers – oil, gas, electricity, biomass/biofuels or hydrogen – and the export of waste streams that result from the energy system, i.e. carbon dioxide. We distinguish energy carriers that are *not available* in Switzerland from those that can be *domestically produced*. The first category includes all fossil fuels and CO_2 storage, which according to recent studies has a very limited domestic potential (Diamond, 2019). The second category comprises electricity, hydrogen and biofuels.

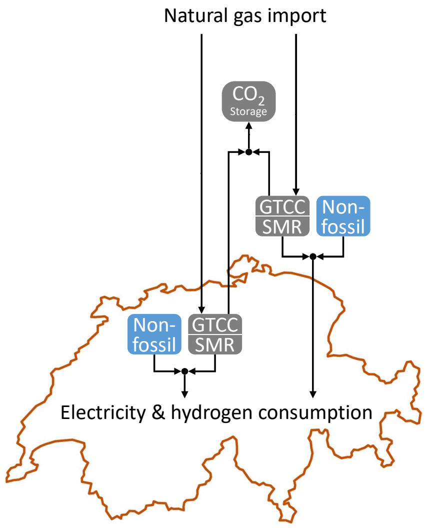
Electricity and hydrogen require special attention in our modelling. Figure 2.1a describes the situation in simple terms. We consider natural gas as the default non-renewable energy source to produce both electricity via combined cycle gas turbines (GTCC) or hydrogen via steam methane reforming (SMR). Both have the option to reduce CO_2 emissions using CCS. In addition, we include non-fossil sources like all renewables for electricity, and electrolysis or wood gasification for hydrogen.

Based on this simplified picture, we can construct two very different options for the modelling of electricity and hydrogen imports. Option A (Figure 2.1b) makes the conservative assumption that non-fossil electricity and hydrogen will not be freely available at sufficient quantity, especially in the winter months. Instead, we assume that electricity and hydrogen are produced outside the Swiss borders with GTCCs and SMR, respectively; and we extend the boundaries of the Swiss system to include these installations abroad and the necessary CO_2 storage. Hence, we include the service from the Swiss neighboring countries in the Swiss energy and CO_2 balance.

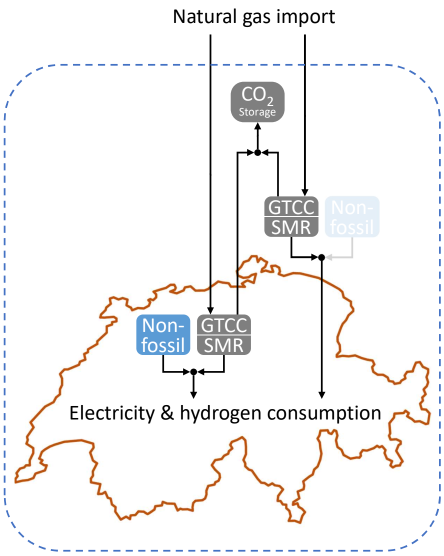
Since the installations inside and outside Switzerland are identical, we do not explicitly distinguish them. The drawback of this approach is that we cannot give any recommendation on whether it is best to deploy certain technologies in Switzerland or abroad. Our results will indicate that Switzerland needs electricity from gas turbines in winter, but not where to locate them. While this is an important limitation, we believe that our results are still relevant for shaping the future energy system, since many of the relevant decisions do not fall into this category, for instance, the production of heat and mobility. Furthermore, we also consider that statements like: *"Switzerland needs biomass gasification to hydrogen - here or somewhere abroad"*, are relevant findings that can lead to concrete actions by the government or by industry.

The second Option B is depicted in Figure 2.1c. Here, we assume that electricity and hydrogen can be freely imported at a certain cost, and that neither the necessary primary energy (e.g. natural gas) nor the resulting CO_2 emissions are attributed to Switzerland. The costs for future electricity imports have been explicitly modeled within JASM (Marcucci et al., 2021b) and the costs for hydrogen are taken from literature (Marcucci et al., 2021b). Limits on cross-border capacity for electricity are also considered. Generally, throughout this report we use the first – more conservative – Option A on how to treat imports of electricity and hydrogen. In Section 5.10 we show the impact of switching to the second Option B, especially the sensitivity to import prices.

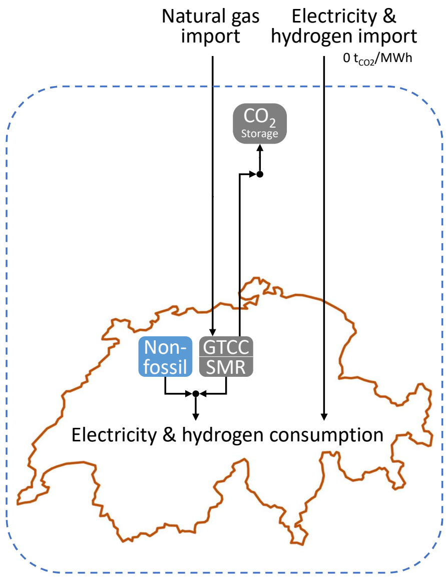
In summary, we assume that Switzerland can import fossil fuels without any limit. We consider the import of electricity and hydrogen, implicitly for Option A, explicitly for Option B. We exclude the import of biofuels or any kind of synthetic e-fuels because they will be scarce even in countries with larger biomass resources than Switzerland. The defining difference along the dimension of market integration is whether or not Switzerland integrates with a European CO_2capture and storage infrastructure.



(a) Simplified representation of cross-border exchanges of electricity and hydrogen.



(b) Option A: consider fossil electricity and hydrogen production abroad on Swiss balance sheet.



(c) Option B: free import of electricity and hydrogen discarding related CO_2 emissions.

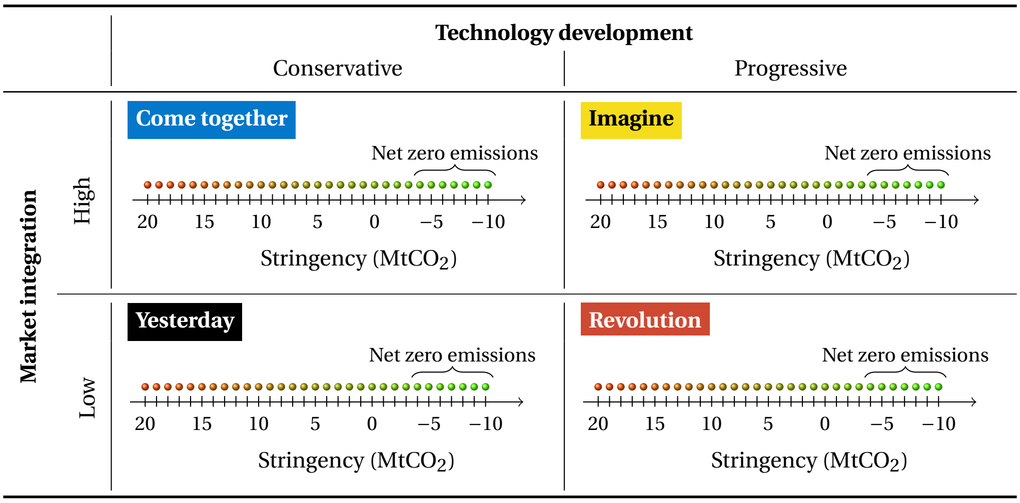
Figure 2.1: Options for the treatment of electricity and hydrogen imports

2.1.4 Scenarios overview

Table 2.2a presents the overview of the scenario variants that we analyze with the SES-ETH model. Each variant corresponds to a combination of the dimensions market integration and technology availability, for which we then evaluate different emission targets, including those of the net-zero emissions scenario (-8 to -4 $MtCO_2$). Table 2.2b presents the differences between the scenario variants regarding the market integration and technology dimensions.

Table 2.2: Scenarios in SES-ETH

(a) Overview



(b) Market integration and technology availability dimensions

Technology or resource	Yesterday	Revolution	Come together	Imagine
Hydro power net growth (TWh/a)	+0	+3.6	+0	+3.6
Storage lake capacity (TWh)	+0	+1.9	+0	+1.9
Wind power (TWh/a)	1.7	4.3	1.7	4.3
Geothermal heat (TWh/a)	0	10	0	10
Forest wood (TWh/a)	7.2	10.9	7.2	10.9
Seasonal high-T thermal storage	no	yes	no	yes
Exports of captured CO_2	no	no	yes	yes

2.2 Monte Carlo analysis

We analyze macro-economic drivers such as population and GDP; global climate change; technology costs; and cost and availability of resources as uncertain factors with probability distributions that we analyze using a Monte Carlo simulation.

2.2.1 Macro-economic drivers and demands

Following the JASM drivers (Marcucci et al., 2021b), we assume a population projection that varies between 9.5 and 10.7 Million people in 2060. Table 2.3 presents the ranges for all the drivers deriving from the population assumptions.

2.2.2 Technology costs

Technology costs are the second type of uncertain variables that we analyze through a probability distribution in a Monte Carlo analysis. Table 2.4 presents the ranges of investment costs for the technologies that we consider of higher uncertainty, the investment costs of the other technologies can be found in Marcucci et al. (2021a).

Table 2.3: Macro-economic drivers in 2060: JASM Variants (Marcucci et al., 2021b,a)

Variable	**Sector**			
	Residential	**Commercial**	**Industrial**	**Transport**
Population (Million people)	9.5–10.7			
GDP ($BCHF_{2010}$)	984.6–1268.9			
ERA (Mm2)	567.8–730.5	242.6–305.5	105.7–115.9	
End use demand				
Space heat - Constant weather	35.2–39.1	15.3–17.1	2.7–3.0	
Space heat - RCP 2.6	34.8–38.6	15.2–16.9	2.7–3.0	
Space heat - RCP 4.5	33.2–36.9	14.5–16.1	2.6–2.8	
Space heat - RCP 8.5	31.0–34.5	13.5–15.1	2.4–2.7	
Warm water	7.0–7.9	2.44–3.12	0.58–0.66	
Process heat		0.26–0.34	17.5–22.8	
Electric appliances	10.3–13.1	11.7–15.2	11.4–14.9	
Passenger transport[a] (Billion pkm)				150.3–187.8
Freight transport (Billion tkm)				38.1–48.1

[a]Including bike and foot

> Data available at https://data.sccer-jasm.ch/macroeconomic-drivers/ and https://data.sccer-jasm.ch/end-use-energy-demand-ses/

Table 2.4: Technology costs in 2060 (Marcucci et al., 2021a)

Technology	**Investment cost**
Electricity production (CHF/kWe)	
Solar PV	500–1500
Waste combined cycle	5000–7000
. With CCS	6800–8800
Wood combined cycle	5000–7000
. With CCS	7160–9160
Combined heat and power (CHF/kWth)	
Sewage sludge CHP	1600–2600
Wood industrial CHP	500–1300
Waste industrial CHP	1600–2600
Heat production (CHF/kWth)	
Wood industrial boiler	500–800
Waste industrial boiler	500–800
Sewage sludge industrial boiler	600–1000
Water source heat pump - Decentralized	1300–3300
Ground source heat pump - Decentralized	1700–3600
Air source heat pump	1200–3000
Solar thermal - medium size	500–750
Solar thermal decentralized	1200–1700
Deep geothermal industrial	2000–4000
Deep geothermal medium size	2000–4000
Hydrogen production (CHF/kWH2)	
Electrolysis Electricity	600–1500

Table 2.4: Technology costs in 2060 (Marcucci et al., 2021a) (continued)

Technology	**Investment cost**
Steam methane reforming (with CCS)	1000–2000
Autothermal reforming	1000–2000
Biomass conversion (CHF/kW)	
Wood gasification + methanation	2300–3500
Wood gasification to H2	1500–2500
. with CCS	1800–2800
Methanation (sabatier)	800–1000

> Data available at https://data.sccer-jasm.ch/energy-conversion-technologies-ses-eth

2.2.3 Costs of resources

We include probability distribution for the costs of imported gas (0.02–0.06 CHF/KWh) and domestic wood (0.04–0.08 CHF/KWh).

2.2.4 Global climate change

Future climate change is an uncertain variable that depends on global economic development and mitigation actions. We use a discrete distribution of the three RCP scenarios (CH2018, 2018) as three possible realizations of the future temperature increase. Based on the climate change scenario we calculate: (1) The climate correction for heating and cooling demands; and (2) The yearly distribution of available hydro inflow for hydropower plants.

2.3 Model, input data and assumptions

Our results are based on the SES-ETH model (Marcucci et al., 2021a) that was developed in ETH based on original SES model (Moret, 2017). The model represents the energy conversion processes and determines the optimal technology mix for a certain emissions target by minimizing the total system costs. SES-ETH includes an hourly resolution that allows us to represent the intra-day variations of the energy demand and resource availability. We include both typical days and intra-day clustering of hours to reduce the computational effort. SES represents the main energy demands: electricity, heating and mobility. SES is a snapshot model, that is, it models the energy system in a target year and it does not make any statements on the trajectory to reach this future state.

A large part of the assumptions in SES-ETH are based on the work of the JASM project. We calculate end-use demands exogenously based on the drivers in (Marcucci et al., 2021b)[3]. The hourly profiles of the different demands are based on Yilmaz et al. (2020). Moreover, we included energy efficiency cost curves from Streicher et al. (2020) for buildings and Zuberi et al. (2020) for the industrial sector. Our assumptions on biomass availability and conversion pathways are based on Marcucci et al. (2021b) and Guidati et al. (2021a). For this work, we use the following additional assumptions:

[3]The demands data can be found at https://data.sccer-jasm.ch/end-use-energy-demand-ses/

- The target year is 2060. This defines all drivers such as population, GDP, climate, biomass availability, etc. (Marcucci et al., 2021b).
- We limit the share of of space heat and domestic hot water supplied to buildings through a district heating network to 30%. We defined several archetypes for single/multi-family houses and district heating schemes that are explained in detail in Section3.2.2.
- We split industrial process heat into medium temperature (< 150 °C) and high temperature (> 150 °C). Moreover, we assume that 1/3 of the total process heat occurs at medium temperature. We defined several archetypes for both categories, that are explained in detail in Section 3.2.1.
- We assume that long distance transport will continue to require a chemical energy carrier. Therefore, we limit the share of electric vehicles that can supply the demand of person- or ton-kilometers. These shares are 80% for passenger vehicles, 50% for buses, and 20% for freight transport. We study the effect of relaxing this constraint in Section 5.6.
- We assume that old buildings can not be easily retrofitted with heat pumps, which we model with a maximum share of heat pumps for single- and multi-family houses of 70%. We also limit the share of air-source heat pumps within the distributed heat pumps to 50%, due to issues as noise emissions. Section 5.4 shows the effect of relaxing this constraint.
- Heat pumps require a heat source at a level generally close to ambient temperature, so-called anergy. For ground source heat pumps, we assume the availability of at most 5 TWh/a of free anergy. Anything above this amount has to first be supplied by regeneration. Water source heat pumps extract thermal energy from lakes or rivers, so we limit the amount of anergy to 10 TWh/a. Section 5.4 studies the effect of reducing the free anergy of the ground to 0 TWh/a.
- Waste incineration plants burn today some 12 TWh/a of waste and supply heat, generally via district heating networks. Since these are long term assets that will exist also in the future, we assume that this level will not drop below 10 TWh/a.
- We assume a discount rate of 2.5%.

2.4 How to interpret the results in this report

Figure 2.2 shows typical results of this approach for a number of output quantities. The Monte Carlo variation of uncertain drivers is represented by showing the median (the white dash), the interquartile range (the colored box) and the minimum and maximum (the lines above and below the box). The x-axis shows the energy-related CO_2 emission (in reverse order, going from high emission targets to low). The four scenario variants are represented by different colors.

2.5 Structure of this report

In the rest of this report we present the insights gained from our scenario analysis and the recommendations that follow from these insights. In chapter 3 we discuss the production and use of energy streams within the energy system. For this analysis, we treat the energy system as the conversion

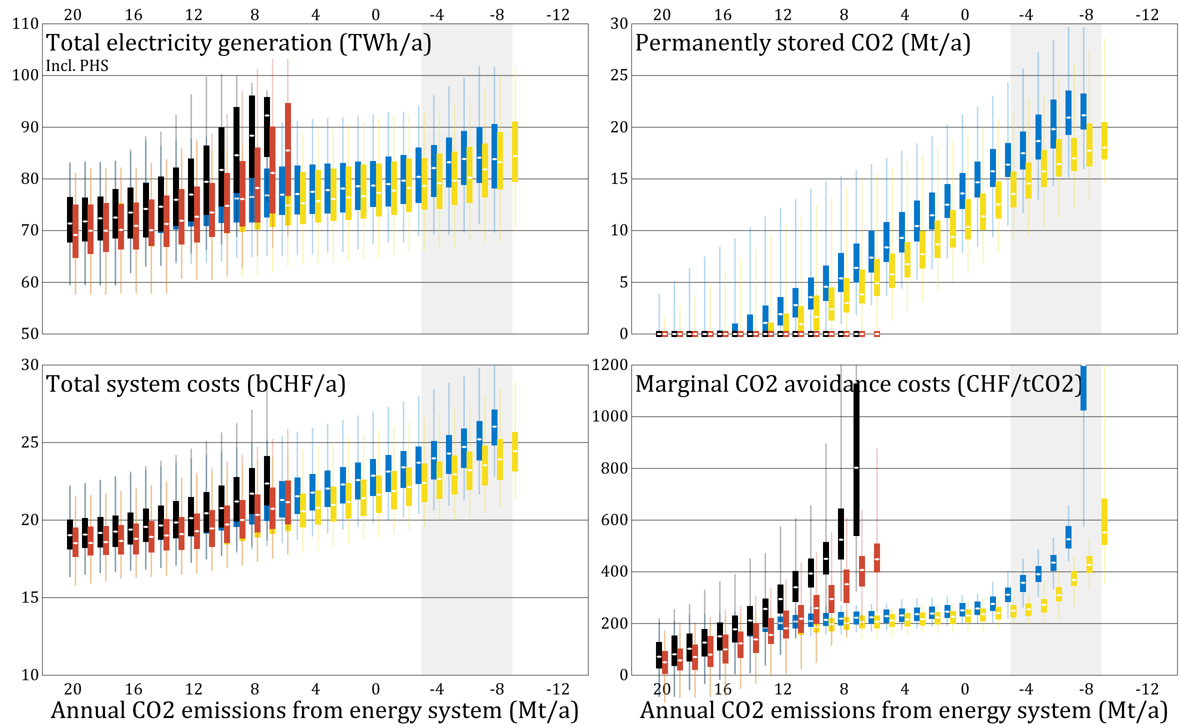


Figure 2.2: Selected model results at different CO_2 targets in the four scenario variants Yesterday, Revolution, Come together and Imagine

of energy from one form to another. We distinguish three energy streams: resources, demands and intermediates, i.e. that are generated from other streams and that are then used to satisfy demands.

In chapter 4 we discuss the balance of CO_2 streams from the point of view of the atmosphere and the subsurface. CO_2 streams are linked to the energy streams, they enter the energy system from the subsurface as fossil fuels (and limestone $CaCO_3$) and from the atmosphere as biomass. They leave the energy system to the atmosphere as emissions and to the subsurface as stored CO_2.

Finally, we address in chapter 5 frequently asked questions related to the energy transition. We first discuss of system costs and marginal carbon prices, as well as the marginal value of certain technologies. We then answer specific research questions, most of them associated to research projects that were related to JASM: What is the future of solar thermal (SFOE project Soltherm2050)? What is the role of hydrogen and CCS (SFOE project Elegancy)? What is the role of storage? What is the best use of geothermal energy (SCCER-SoE)? The reader may decide to skip the details in Chapter 3 and go directly to Chapter 5 that makes heavy reference to the previous one.

Chapter 3

Energy streams

In this chapter, we discuss the production and use of energy streams within the energy system. For this analysis, we treat the energy system as the conversion of energy from one form to another. We distinguish three energy streams (Table 3.1):

- Streams that enter the energy system as available resources. For these energy carriers we answer the questions of *How is it used?*
- Streams that exit the energy system in the form of an end-use demand. Here the question is *How is it produced?*
- Streams that act as intermediates, i.e. that are generated from other streams and that are then used to satisfy demands. Here both questions apply.

Table 3.1: Energy streams

	How is it produced?	Where is it consumed?
Resource streams		
Dry biomass (wood)		Domestic heat, CHP, process heat, gasification
Wet biomass (manure, green waste, sewage sludge)		Fermentation
Waste		CHP in district heating, industrial process heat
Geothermal		District heat, process heat, electricity
Solar thermal		Domestic and industrial heat
Intermediate streams		
Methane	Imports, fermentation, gasification	Power generation, CHP, combustion
Hydrogen	Electrolysis, reforming, gasification, imports	Electricity and heat production, mobility
Electricity	PV, wind, geothermal, hydropower, thermal power	Electricity appliances demand, heat pumps, electric heater, e-mobility, electrolysis
Carbon dioxide	Fermentation, gasification, reforming, separation	Synthesis, geological storage
Demand streams		
Domestic heat	Combustion, geothermal, solar thermal, heat pumps	
Process heat	Combustion, geothermal, solar thermal, electric heaters	

Table 3.1: Energy streams (continued)

	How is it produced?	Where is it consumed?
Passenger mobility	Battery electric, fuel cell electric and internal combustion vehicles	
Freight mobility	Battery electric, fuel cell electric and internal combustion vehicles	

To give an example, geothermal energy corresponds to the first type. It may be used for district heating or low temperature process heat (*How is it used?*, Figure 3.3 on page 20). The demand for low temperature process heat corresponds to the second stream. It can be produced using geothermal energy, solar thermal, wood boilers, etc. (*How is it produced?*, Figure 3.7 on page 26). Therefore, an energy form like geothermal appears in both sections on resource streams and demand streams.

Note that we also avoid using items like district heat (german *Fernwärme*) as energy forms, as it is commonly done in energy statistics. We focus instead on the real energy streams, e.g. waste - turned into heat - used to satisfy a heat demand. This approach allow us to easily distinguish final energy and useful energy demand. All demand streams, like the aforementioned low temperature process heat are useful energy demands. The wood that is consumed by a boiler to produce heat is the final energy demand. The difference between the useful and the final energy demand is given by the efficiency of the boiler.

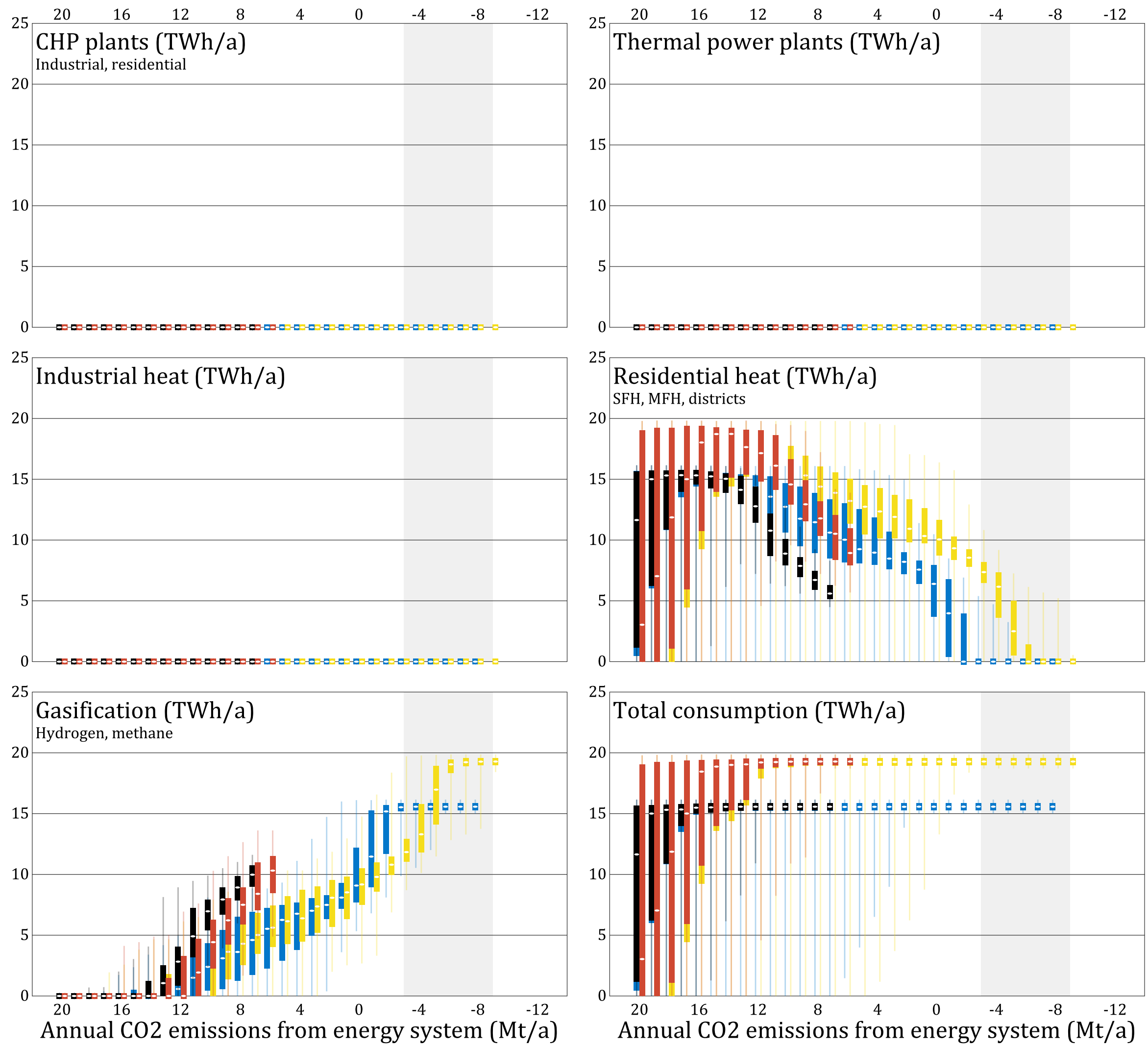
3.1 Resource streams

3.1.1 Biomass

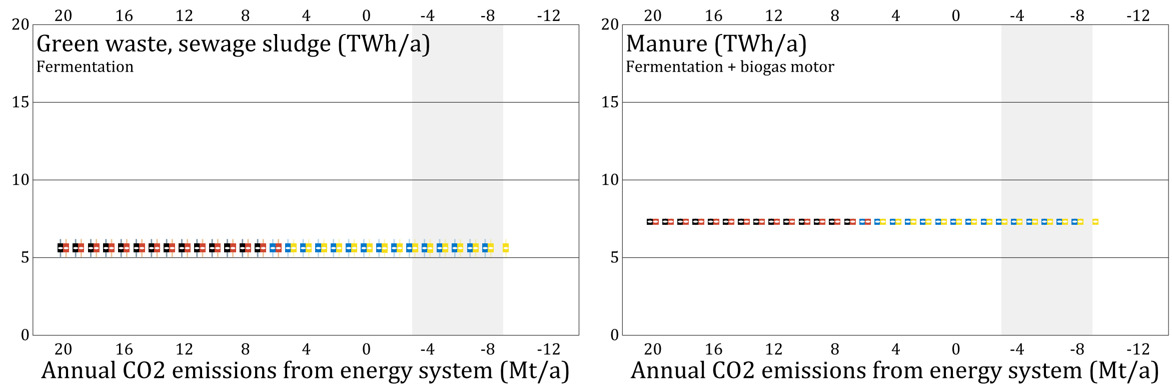
Biomass is the main source of CO_2-neutral hydrocarbons, it includes wood, green waste, animal manure and sewage sludge. The future potentials for biomass are based on a joint study of JASM and the SCCER-Biosweet (Guidati et al., 2021a). Based on the conversion routes in Guidati et al. (2021a), we model alternative conversion pathways for the different biomass categories. Wood can be combusted to produce power and heat or gasified to synthetic natural gas or hydrogen. Manure can be used in anaerobic digestion that produce raw biogas to be used in small internal combustion engines to produce electricity and heat. The latter is used on-site as much as needed and the rest is discarded. We assume that at most 10 % of the biogas produced in such installations could actually be fed into a gas grid. Since this is a negligible quantity, we assume that only central anaerobic digestors that process green waste and sewage sludge plants are connected to a gas grid. Green waste can be used in central anerobic digestors that produce biogas that is upgraded to syntetic natural gas; or combustion plants. Finally, current Swiss regulations enforce the energetic use of sewage sludge from waste water treatment plants with a cascade utilization (Thees et al., 2017, p. 279). The fresh sewage sludge undergoes goes first to an anaerobic digestor that produces biogas, which can be used on-site or injected into the gas grid after gas cleaning. The residual sludge is then combusted in waste incineration plants, specialized sludge incinerators and cement plants.

All biomass conversion pathways are carbon neutral and can be carbon negative if the CO_2 is separated and stored permanently from the biosphere through geological storage (BECCS).

Today, wood is largely used in furnaces to generate heat, ranging from single-, multi-family houses and districts heating schemes, to industrial installations for process heat. We find in our scenarios,



(a) Wood



(b) Wet biomass

Figure 3.1: Use of biomass in scenario variants Yesterday, Revolution, Come together, Imagine

that the use of wood will be shifted from combustion to gasification plants to produce hydrogen and negative CO_2 emissions (Figure 3.1a). This shift is triggered by the net-zero emissions target (see also section 3.3.1). For the lowest CO_2 targets, wood is used up to its maximum potential.

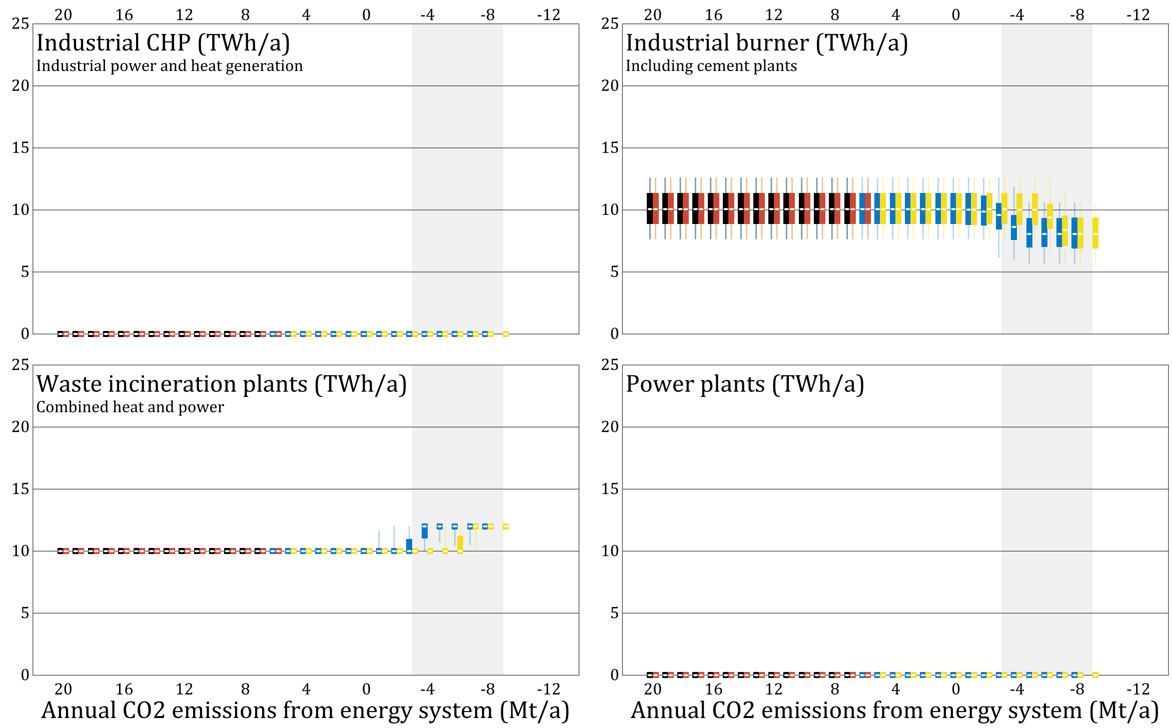


Figure 3.2: Use of waste in scenario variants Yesterday, Revolution, Come together, Imagine

It might appear surprising that our results do not include the use of wood to generate process heat in industry. The reason is that the model foresees a wider range of options for this sector, such as waste or hydrogen. Moreover, it is also worth noting that in none of our scenarios wood is used for electricity generation, neither with CHPs nor power plants. The reason is that cost of electricity generation is high due to high investment costs and low capacity factors, since extra electricity is needed only in winter months. One exception is studied in Section 5.9: when wood gasification is excluded from the energy system, wood power plants with CCS are the second best option (in economic terms) to generate negative CO_2 emissions.

All 6 TWh/a of sewage sludge and green waste are used in anaerobic digestors (Figure 3.1b). These are used to produce around 2 TWh/a of bio-methane (Figure 3.25 on page 48). This is a twofold increase from today's level, which is driven by three factors: (i) higher population, (ii) higher collection rate (i.e. a better separation of green waste from the waste that is incinerated), and (iii) a shift from composting to fermentation. All manure is processed in distributed rural anerobic digestors where the biogas is directly used in small combined heat and power plants.

3.1.2 Waste

Waste, like biomass, is a valuable resource for the future energy system given its content of chemical energy and carbon. The categories of waste and biomass are overlapping since an important portion of waste is actually biomass, i.e. the green waste not separated in the municipal waste or animal residues in cement plants. In SES-ETH, we use the long-term potentials for waste calculated by Guidati et al. (2021a). They estimated 17–21 TWh of the sustainable potentials for energy use of waste, including both the green part (of biogenic origin that can be separated by the households) and the mixed part (that includes both fossil and organic waste and is not separated).

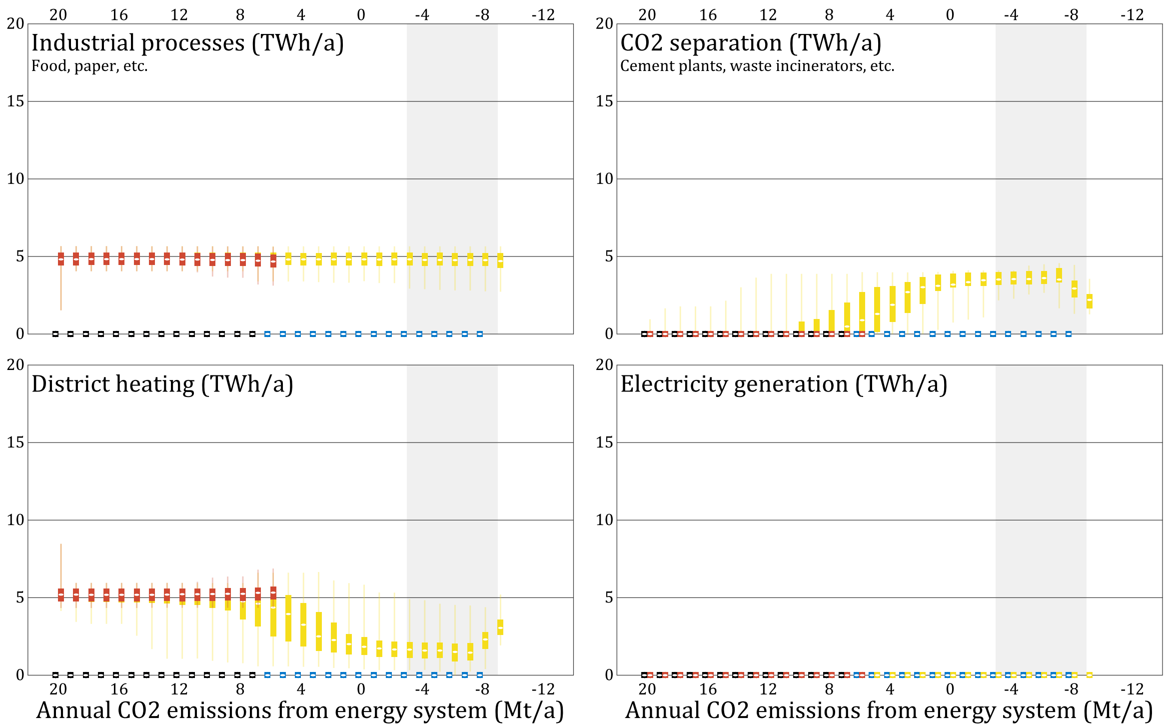


Figure 3.3: Use of geothermal heat in scenario variants Yesterday, Revolution, Come together, Imagine

Figure 3.2 shows that, in the decarbonization scenarios, waste is used as today in waste incineration plants and in industry to generate process heat by combustion. Today, around 12 TWh/a of waste are burned in waste incinerators, which are mainly linked to district heating networks. We assume that this level will stay at least at 10 TWh/a, since these are expensive assets with a long lifetime. The additional waste potential linked to growing population and GDP goes to industrial heat generation, compensating to some extent the reduction in the use of natural gas and oil that is no longer available in a net-zero scenario (Figure 3.5).

3.1.3 Deep geothermal

Geothermal energy exploits the sensible heat that is stored in the rock masses below our feet. Temperature increases with depth, in Switzerland this so-called geothermal gradient is approx. 30 °C/km. Ground source heat pumps exploit the heat in a layer between 0 and approx. 500 m depth. Anything deeper is called deep geothermal. A common feature of all heat exploitation in the underground is that it is normally not regenerated at a similar rate as its usage, since the geothermal heat flow from the deeper layers is only 0.1 W/m2.

Deep geothermal energy can be used directly as heat for districts or low-temperature industrial processes. Depths of 3 km are sufficient for temperatures up to 100 °C. Greater depth can deliver higher temperatures, which can in principle be used to generate electricity in organic Rankine cycles. However, the conversion efficiency of heat to electricity will be low in the order of 10-15 %.

Our analysis assumes an availability of 10 TWh/a (Table 2.2b) of deep geothermal heat at temperatures that would allow for all aforementioned usage options: district heating, industrial processes

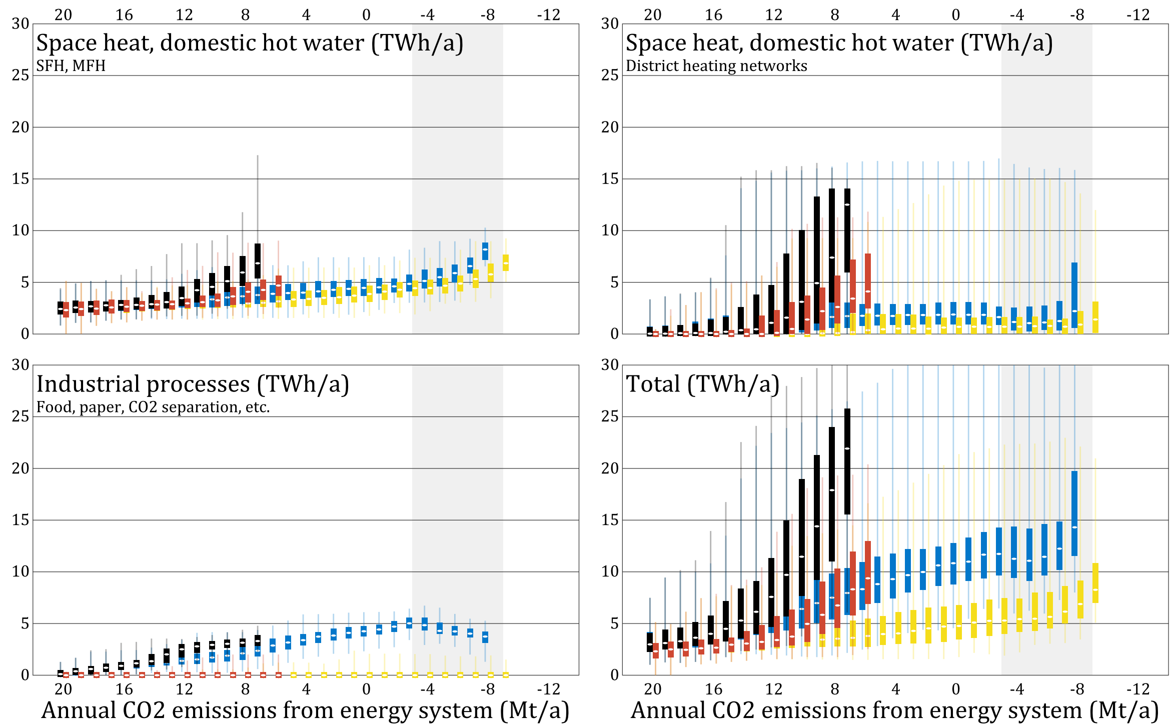


Figure 3.4: Use of solar thermal heat in scenario variants Yesterday, Revolution, Come together, Imagine

and electricity generation. The 2012 Swiss Energy Strategy (Prognos, 2012) assumed 4.4 TWh/a of geothermal electricity. Given the low conversion efficiency, this would require around 35–40 TWh/a of geothermal heat. Hence, our assumption of 10 TWh/a is a conservative one.

Figure 3.3 shows the use of geothermal heat. The model chooses to use it mostly to supply low temperature in industrial processes. When CCS and geothermal are available (Imagine), a large portion of geothermal energy is used in the desorption process of a CO_2 capture plant. When CCS is not available (Revolution), geothermal heat is used for district heating. Note, that geothermal electricity generation is never chosen.

These results require some careful interpretation: geothermal heat extraction has large investment but low operation costs. It is therefore a logical choice for industrial processes because these require a large amount of full load hours per year. However, industries are sensible to market conditions and using geothermal energy to supply industrial heat only has the risk of becoming an expensive stranded asset if the end-user needs to shut down. On the contrary, a town or city using district heating with geothermal is unlikely to disappear. Hence, we consider reasonable, from the investor perspective, a more balanced use of geothermal energy for heating and industrial processes.

3.1.4 Solar thermal

Solar thermal collectors are an alternative source for the production of low-temperature heat. We model this option for single- and multi-family houses, district heating, low temperature industrial processes and the special case of CO_2 separation. We assume that solar collectors can always be combined with a short term or a seasonal thermal energy storage. A special option for these seasonal thermal storage is a solar ice system, where a heat pump and a solar collector are combined with a seasonal ice storage (Archetype DEC3 in section 3.2.2).

Figure 3.4 shows the uses of solar thermal in our scenarios. We find that solar thermal has a larger use in the scenario variants in which geothermal is not available (Yesterday and Come together). In Yesterday, the deployment increases significantly with the stringency of the target. This larger deployment implies a large increase in the system costs (see Section 5.1). For the net-zero emissions targets (-4 to -8 Mt_{CO_2}/a), the use of solar thermal heat is 10–15 TWh/a in Come together and 5–8 TWh/a for Imagine (when geothermal is available). Most of the solar thermal heat is used to supply industrial processes, CO_2 separation, space heat and domestic hot water.

In summary, we find that solar thermal energy can play an important role in a net-zero scenario. Naturally, it must be complemented with another supply solution and thermal storage to balance the day-night variation. Therefore, it seems a less attractive option than geothermal that can deliver heat on demand. Nevertheless, an important advantage of solar thermal is its maturity level, given that it is a technology available in the market, whereas deep geothermal energy has yet to be demonstrated at large scale (see also Section 5.4).

3.1.5 Recommendations for the use of future resource streams

- Biomass and waste are key resources to generate electricity and heat, and even more important to produce negative CO_2 emissions through gasification and CCS.

- The usage of wood shifts from today's combustion to hydrogen production through gasification for the lower CO_2 targets. This trend is triggered by the need for hydrogen (Section 3.3.1) and the need for capturing biogenic CO_2 to realize negative emissions (Chapter 4). Wood is always used up to the maximum potential. **Therefore, a forest management strategy that leads to highly available wood resources is essential for the realization of the net-zero GHGs emissions goal**.

- Two new low temperature heat sources should be exploited, geothermal and solar thermal heat. Both may be used for domestic heating and low temperature industrial processes including the desorption in CO_2 capture plants. The most recent insights into the soft stimulation of geothermal reservoirs must be put into practice to reduce the exploration risk associated to this new energy source. **Our model results suggest that priority should be given to direct heat utilization instead of electricity production**. Despite the issue of seasonality, solar thermal heat plays an important role, especially if no geothermal heat is available.

- The production of bio-methane in anaerobic digestors that process green waste, crop residues and sewage sludge should be intensified by (i) increasing the collection rate, i.e. reduce the amount of green waste that ends up in waste incinerators, and (ii) by switching from composting to fermentation. The largest unexploited resource is manure. This should be used in rural fermentation plants and directly converted into electricity and heat if no gas grid is nearby.

- Waste is increasingly used to generate process heat. This may pose a challenge when easier fuels such as oil and gas need to be replaced.

3.2 Demand streams

3.2.1 Process heat

Roughly half of the final energy consumption of the industrial sector is for process heat generation, ranging from 80 °C for food, pulp and paper up to 1500 °C for cement production. We model six archetypes for process heat: three for the medium temperature range (80 – 150 °C) (MTH1–3), and three for the high temperature range (150 – 1500 °C) (HTH1–3) (Table 3.2). Our demands for process heat are based on an extrapolation of the demand per unit of GDP using the macro-economic harmonized drivers from the JASM assumptions (Guidati et al., 2021b, Appendix B). We assume a split in the demand between medium and high temperature range of 1/3 and 2/3, respectively. In addition, we model the option to separate CO_2 from the flue gas of combined cycle gas turbines (GTCC), municipal waste incineration plants (KVA in German), cement plants (cement), and gasification and gas reforming plants (Gasi/Ref). The separation process requires a substantial amount of medium temperature process heat, hence we include these four technologies in the archetypes for the demand of process heat (Table 3.2).

Table 3.2: Process heat archetypes in the SES-ETH model

Archetype	**Medium temperature**			**High temperature**			**CO_2 separation**			
	MTH1	**MTH2**	**MTH3**	**HTH1**	**HTH2**	**HTH3 (Cement)**	**GTCC**	**KVA**	**Cement**	**Gasi/Ref**
Gas/liquid boiler				x						
Solid fuel boiler					x	x				
Gas/liquid CHP	x						x			x
Solid fuel CHP		x						x		
Geothermal			x					x	x	x
Solar thermal	x	x	x					x	x	x
Electric heater	x	x	x	x						
Heat storage	x	x	x	x			x	x	x	x

Annual demand

Figure 3.5 shows the supply mix for high temperature process heat (excluding cement plants). For moderate CO_2 targets of more than 10 $MtCO_2$/a, our results show an equal mix of liquid/gaseous fossil fuels and waste. For CO_2 targets approaching the negative range, these technologies are replaced by hydrogen and electric heating. Figure 3.6 depicts the supply of the additional high temperature heat required for cement plants. Comparing figures 3.5 and 3.6 indicates a switch of waste combustion from the general high temperature processes (HTH2) to cement plants (HTH3), more specifically to the CO_2 separation, not the main calcination process (Figure 3.6). This suggests an interesting option of moving the special waste incineration plants close to the cement plants to supply heat for the CO_2 separation process.

Figure 3.7 on page 26 shows the supply mix for medium temperature process heat. More options are available in this temperature range, including besides direct combustion and electrical heating, the heat from CHP units and solar and geothermal. Especially the latter has a remarkable impact. For the two scenarios that include the deployment of geothermal heat (Imagine and Revolution), a

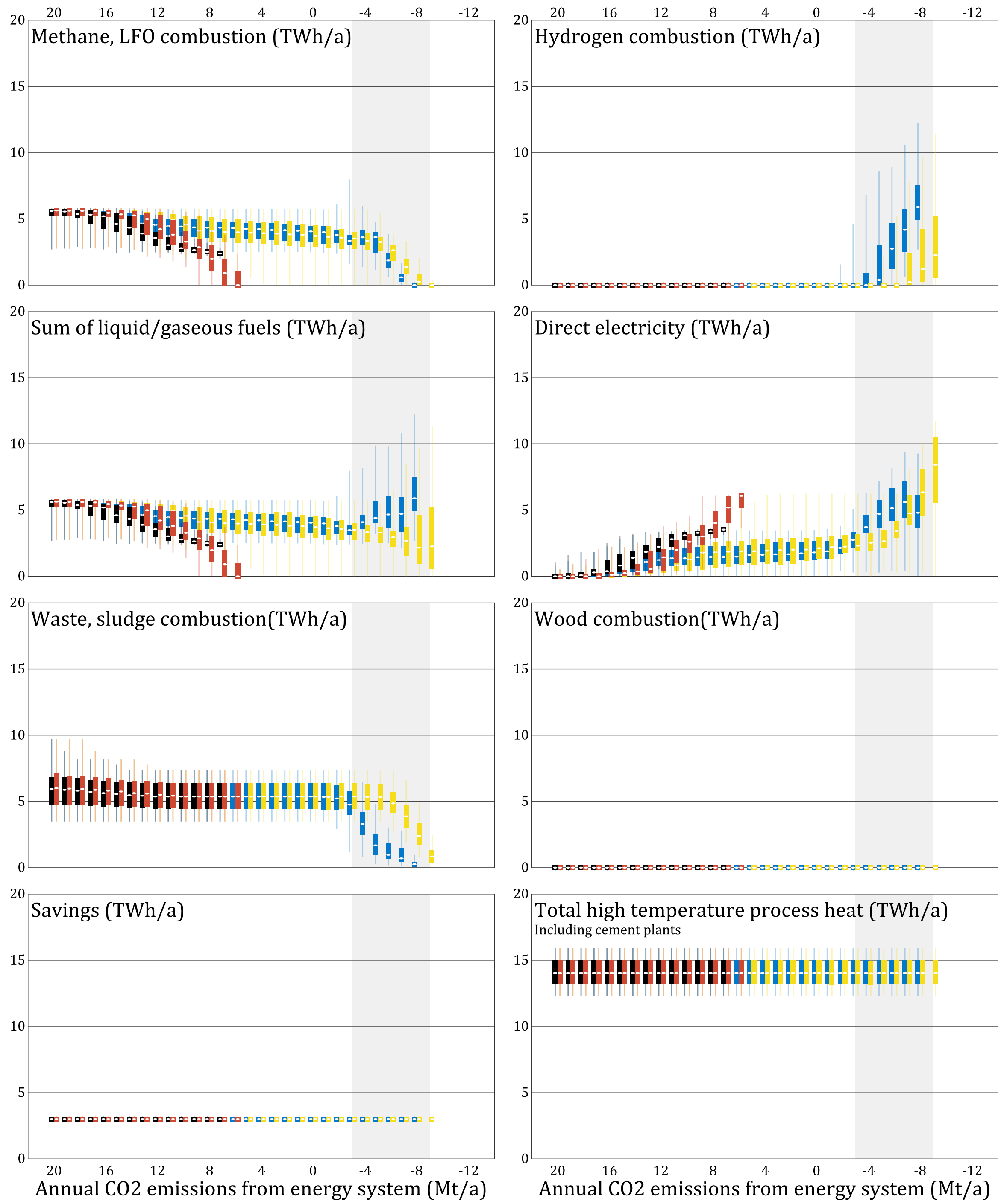


Figure 3.5: Supply of high temperature (> 150 °C) process heat for scenario variants Yesterday, Revolution, Come together, Imagine

large fraction of the demand is covered by this source. When geothermal is absent (Yesterday and Come together), solar thermal makes an important contribution, together with gas-fired CHP units that switch from fossil fuels to hydrogen for lower CO_2 targets.

For both medium and high temperature heat, we model the possibility to deploy efficiency measures in terms of a total potential (TWh/a) with the corresponding investment costs (Marcucci et al., 2021a). In the results, we show these energy efficiency measures as a virtual heat sources (labelled Savings).

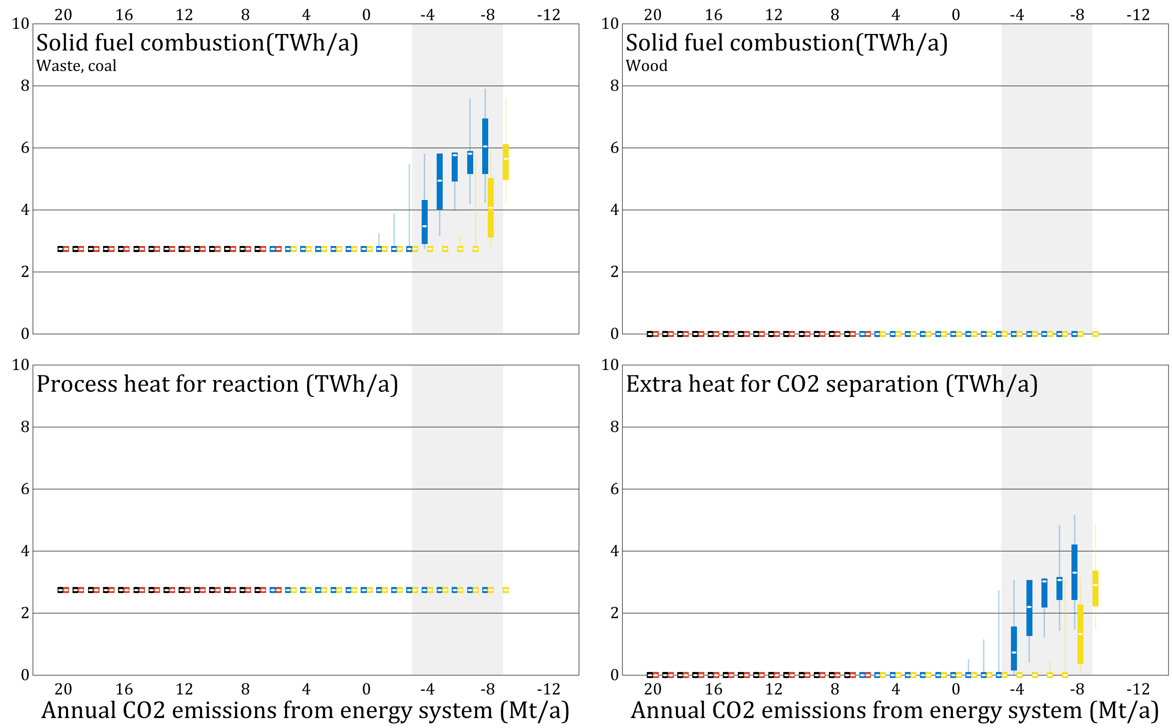


Figure 3.6: Supply of high temperature process heat for cement plants for scenario variants Yesterday, Revolution, Come together, Imagine

We find that the maximum potential for energy efficiency savings is always chosen, demonstrating that they are cost effective - compared to all other options needed to reduce CO_2 emissions.

Finally, Figure 3.8 summarizes the sources of heat for the CO_2 separation process. The most important insight is that the total heat required for separation is in the order of 10 TWh/a.

Yearly patterns

Figure 3.9 on page 28 shows the yearly patterns of high temperature process heat for a representative case of the four scenario variants. The CO_2 targets are 9, 7, -6 and -6 Mt/a for Yesterday, Revolution, Come together and Imagine, respectively. These CO_2 targets correspond to the lowest feasible CO_2 emissions of each scenario variant. Electric heating plays an important role, especially in summer when photovoltaic generation is strong. It is supported by a short-term thermal energy storage to balance the diurnal variation. When high temperature seasonal energy storage is available (Revolution and Imagine), some of the heat that is generated in summer can be shifted to winter to reduce consumption of fossil oil and gas. For medium temperature process heat, solar thermal plays a similar role in those scenarios in which geothermal heat is not available (Yesterday and Come together (Figure 3.10 on page 29).

Also in the special case of medium temperature heat for CO_2 separation, a fluctuating energy source like solar thermal is integrated with the help of a thermal storage (see Figure 3.11 on page 30 for waste incineration plants). Most of the heat for waste incineration plants and gas turbines can be extracted from their core process (although it cannot be used for district heating or for electricity generation). For a cement plant, extra heat has to be generated. For Come together this extra heat comes from

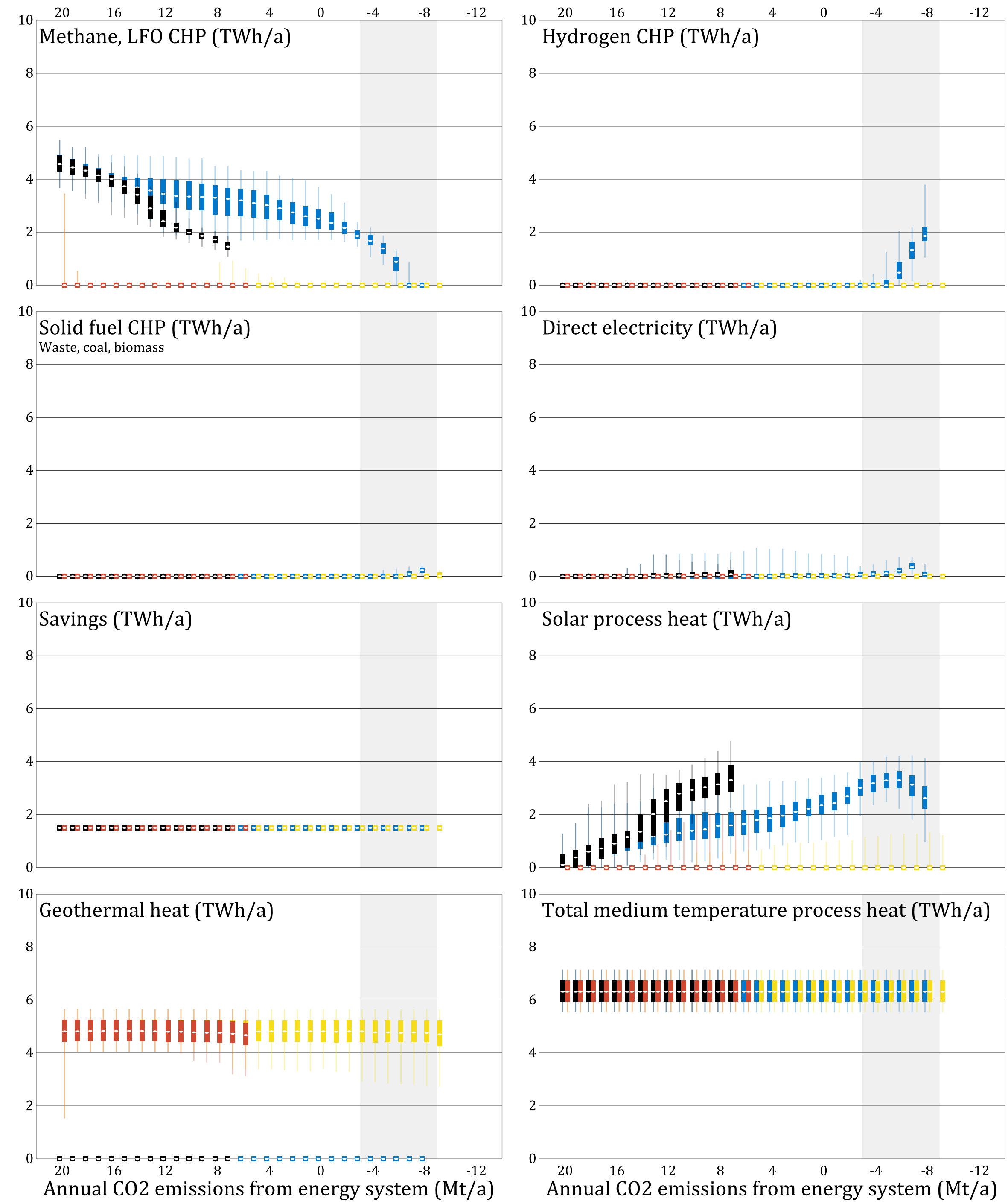


Figure 3.7: Supply of medium temperature (< 150 °C) process heat for scenario variants Yesterday, Revolution, Come together, Imagine

extra combustion of waste (bottom row of Figure 3.6 on the previous page). For Imagine, geothermal energy is available, which covers the full heat demand for CO_2 separation.

A common pattern emerges from the three process heat cases: the basic supply is achieved through combustion of methane or hydrogen, waste, or by using geothermal energy. An additional fluctuating energy source - electricity for high temperature, solar thermal for low temperature - is used in conjunction with a thermal storage to save the otherwise limited main resource. It is important to note

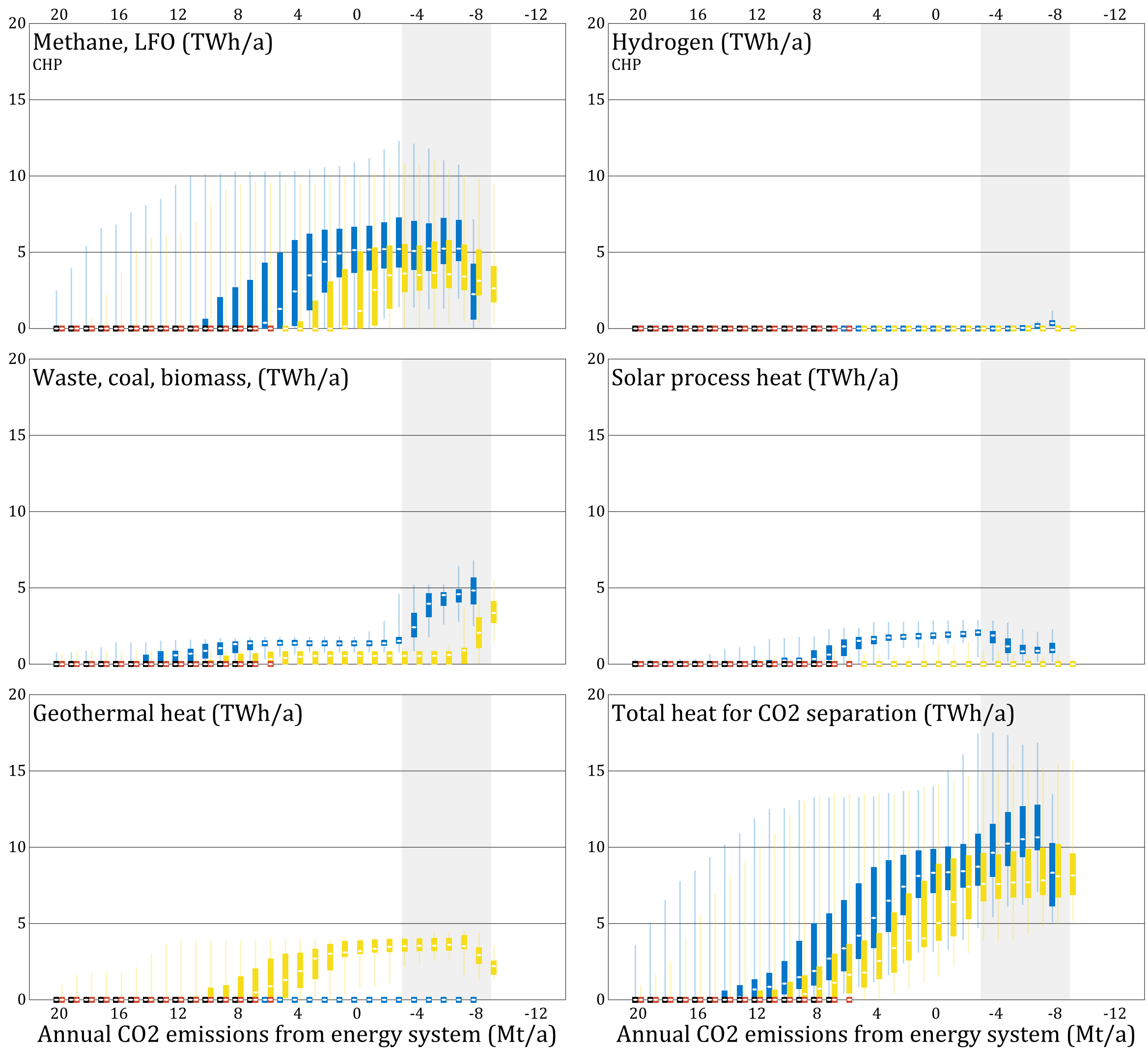


Figure 3.8: Supply of medium temperature (< 150 °C) heat for CO_2 separation processes; scenario variants Yesterday, Revolution, Come together, Imagine

that we assume that geothermal energy is a limited resource. In principle, once a geothermal reservoir has been accessed through an appropriate combination of injection and production boreholes, the heat can be extracted continuously. However, since the reservoirs have a limited size and the natural heat flux in the earth is too low to regenerate the reservoir at the same rate as heat is extracted, we consider geothermal energy as a limited resource. Therefore, saving this resource during the summer months by exploiting solar thermal simply prolongs the lifetime of the reservoir.

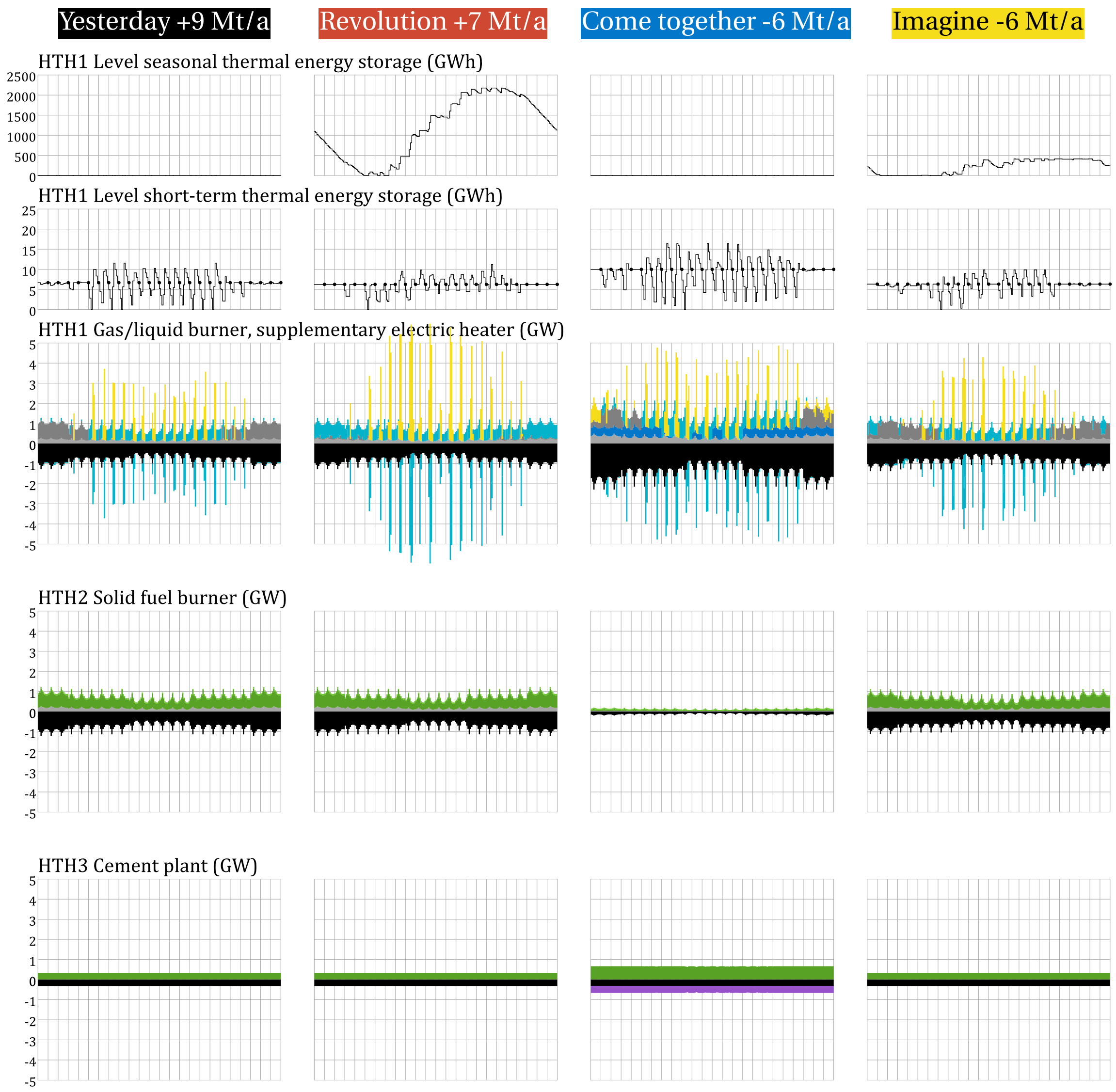


Figure 3.9: High temperature process heat for a typical case of the four scenario variants: Thermal storage, electric heater, fossil fuel, efficiency, hydrogen, biomass, waste, demand, and CO2 capture in cement plant

Figure 3.10: Medium temperature process heat for a typical case of the four scenario variants: Electric heater, solar thermal, biomass, waste, geothermal, hydrogen, efficiency, fossil fuel, demand, and thermal storage

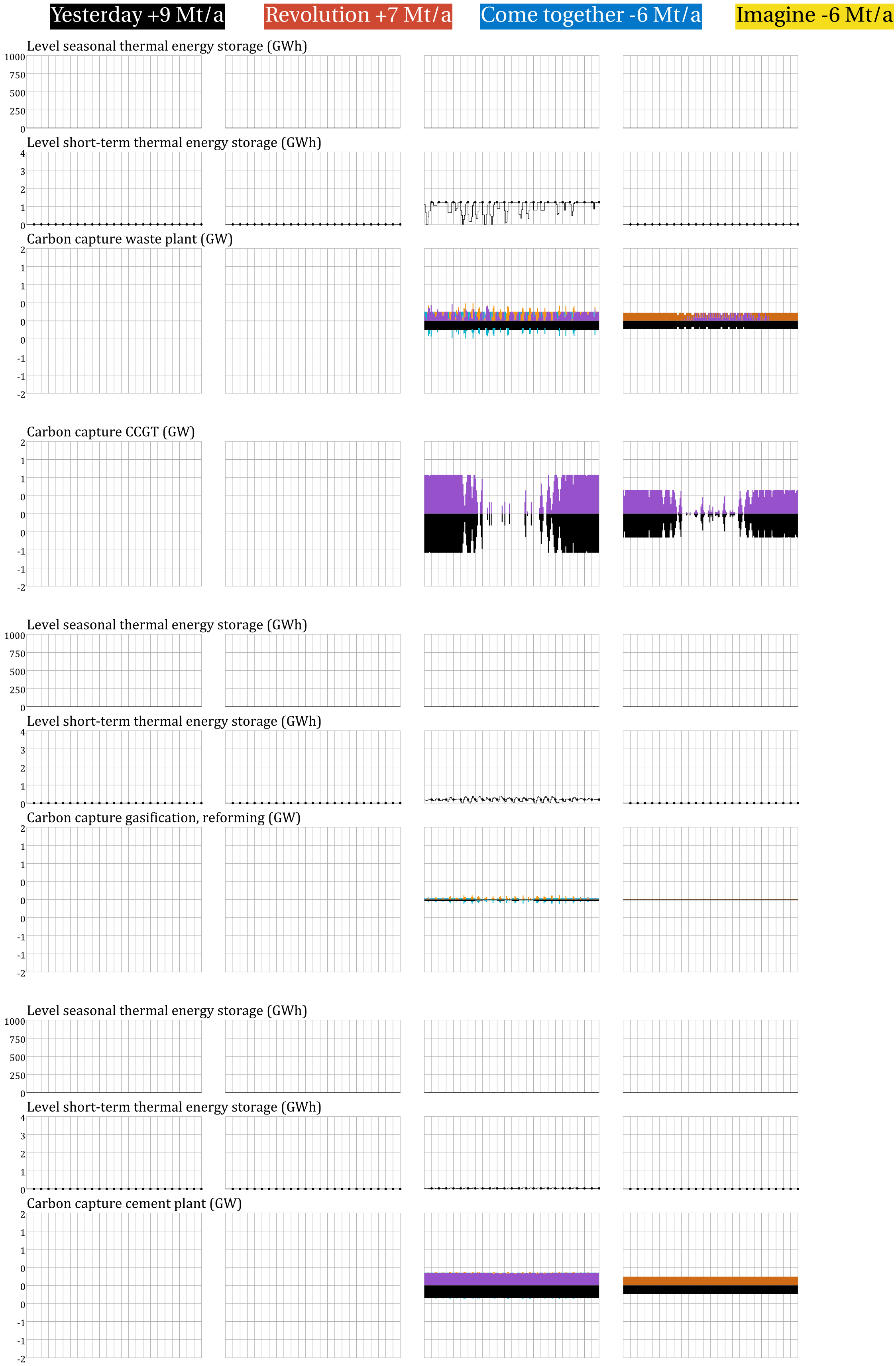


Figure 3.11: Medium temperature heat for CO_2 separation process for a typical case of the four scenario variants: From core process, solar thermal, geothermal, hydrogen, fossil fuel, demand, and thermal storage

3.2.2 Space heat and domestic hot water

We calculate the future demand for space heating using a model that takes into account the growth of building stock, the replacement of old buildings, the consumption per unit of area and the impact of climate change (Marcucci et al., 2021a). For domestic hot water, we extrapolate the demand per capita using the population projection of the harmonized JASM drivers (Marcucci et al., 2021a). In SES-ETH, we split the demand for space heating and domestic hot water into six archetypes for district heating (DHN1–6), and six archetypes for single and multi family houses (DEC1–6) (Table 3.3).

Table 3.3: Domestic heat archetypes in the SES-ETH model

Archetype	**DHN1**	**DHN2**	**DHN3**	**DHN4**	**DHN5**	**DHN6**	**DEC1**	**DEC2**	**DEC3**	**DEC4**	**DEC5**	**DEC6**
Wood CHP plant	x											
Waste CHP plant	x											
CH4 boiler	x									x		
H2 boiler	x											
LFO boiler	x										x	
CH4/H2 CHP plant		x										
Wood boiler			x									x
Biogas motor				x								
Water heat pump					x				x			
Air heat pump								x				
Ground heat pump							x					
Electric heater					x		x	x	x			
Geothermal						x						
Solar thermal	x	x	x	x	x	x	x	x	x	x	x	x
Daily storage							x	x	x	x	x	x
Seasonal storage	x	x	x	x	x	x	x		x			

DHN1 is the classical example of a waste incineration plant connected to a district heating network. DHN4 models a biogas CHP plant with a small rural heat network. DHN5 represents a heat pump that draws energy from a body of water, for instance a river or a lake. We assume a maximum potential of 10 TWh/a for the free low temperature heat in the bodies of water. In this case, we do not distinguish the option of having a centralized heat pump that distributes heat at the end-use temperature level, or an anergy grid where cold water is supplied to distributed heat pumps.

DEC1 represents the typical ground source heat pump that is very common in Switzerland. Here we assume that at most 5 TWh/a are available as free low temperature heat in the ground. Everything beyond that value requires regeneration of the borehole field, for instance by solar thermal collectors. An alternative to the ground source heat pump is a solar ice system that is modelled as DEC3. Here, the low temperature source of the heat pump is an ice storage that needs to be charged by solar thermal collectors. DEC2 is the classical air source heat pump, which draws energy from the ambient air. This energy from the air is in principle unlimited but suffers from lower efficiency and other issues as noise emissions.

We introduce some additional assumptions in SES-ETH: The total share of district heating is limited to 30%. We assume for the remaining 70% of decentralized generation, that at most 70% can be supplied to heat pumps. This takes into account the fact that old buildings will continue to be part of the building stock and they are they cannot be easily retrofitted with heat pumps, since that generally requires underfloor heating. Finally, we limit the share of air-source heat pumps (DEC2) within the distributed heat pumps (DEC1-3) to 50%, due to issues as noise emissions[1]. In Section 5.4 we study the effect of releasing some of these assumptions.

Annual demand

Figure 3.12 shows the technology mix for district heating networks. Around 5 TWh/a come from waste incinerators, a number that is similar to today's production. Water source heat pumps use large bodies of water as source of anergy, e.g. lakes or rivers. Generally, the maximum potential of 10 TWh/a of low temperature heat are used, the higher values in Figure 3.12 include the electrical consumption of the heat pumps itself. Geothermal heat is mostly used in Revolution for district heating, while in Imagine the use of geothermal is lower because part of the heat goes to the CO_2 separation process from cement plants and waste incinerators (Figure 3.8 on page 27).

Figure 3.13 shows the technology mix for single and multi-family houses. As expected, our results show a strong contribution of heat pumps, both air and ground source. Wood combustion is important for moderate CO_2 targets of > 10 $MtCO_2$/a but reduces strongly in the range of negative emissions, due to the switch to wood gasification (Section 3.1.1). Oil and gas boilers are used for high emission targets (15–20 Mt/a), then they disappear and emerge again for targets below 0 Mt/a. This seemingly erratic behavior is caused by the strong growth of negative emissions due to wood gasification that allows for the use of some gas for heating in the range below 0 Mt/a. Solar thermal produces around 5 TWh/a.

We find that the split between district heating and distributed generation is always limited by our assumption on the maximum share of district heating of 30%. As for industrial heat supply, we model building renovation for residential buildings as a maximum potential with a corresponding investment cost (Marcucci et al., 2021a), which we represent with an optional virtual heat source. For all scenarios and CO_2 targets, a large part of the maximum allowed value of 23.7 TWh/a of savings is chosen, showing that building renovation is a cost effective means to reduce GHG emissions. Figure 3.14 splits the total supply of space heat and domestic hot water into the major categories: combustion, heat pumps and solar/geothermal and building renovation. Again, the various types of heat pumps are the dominant supply technology.

Yearly patterns

Figures 3.15 to 3.18 show the yearly patterns of heat supply for a representative case of the four scenario variants. The district heating archetype DHN1 shows the operation of a waste incineration plant. In all cases, a seasonal thermal energy storage uses the excess heat that is generated in summer and stores it for the winter months. For Yesterday and Revolution, we find that a solar thermal generation is additionally used to charge the thermal storage.

DHN4 represents a comparable case of a district heating network supplied by biogas motors. Again, the use of a seasonal thermal energy storage is beneficial.

We find that large water source heat pumps in DHN5 are deployed for all scenario variants, always combined with a seasonal thermal energy storage. The contribution is lowest for variant Revolution,

[1] Note that all of these assumptions could be improved with additional buildings stock models.

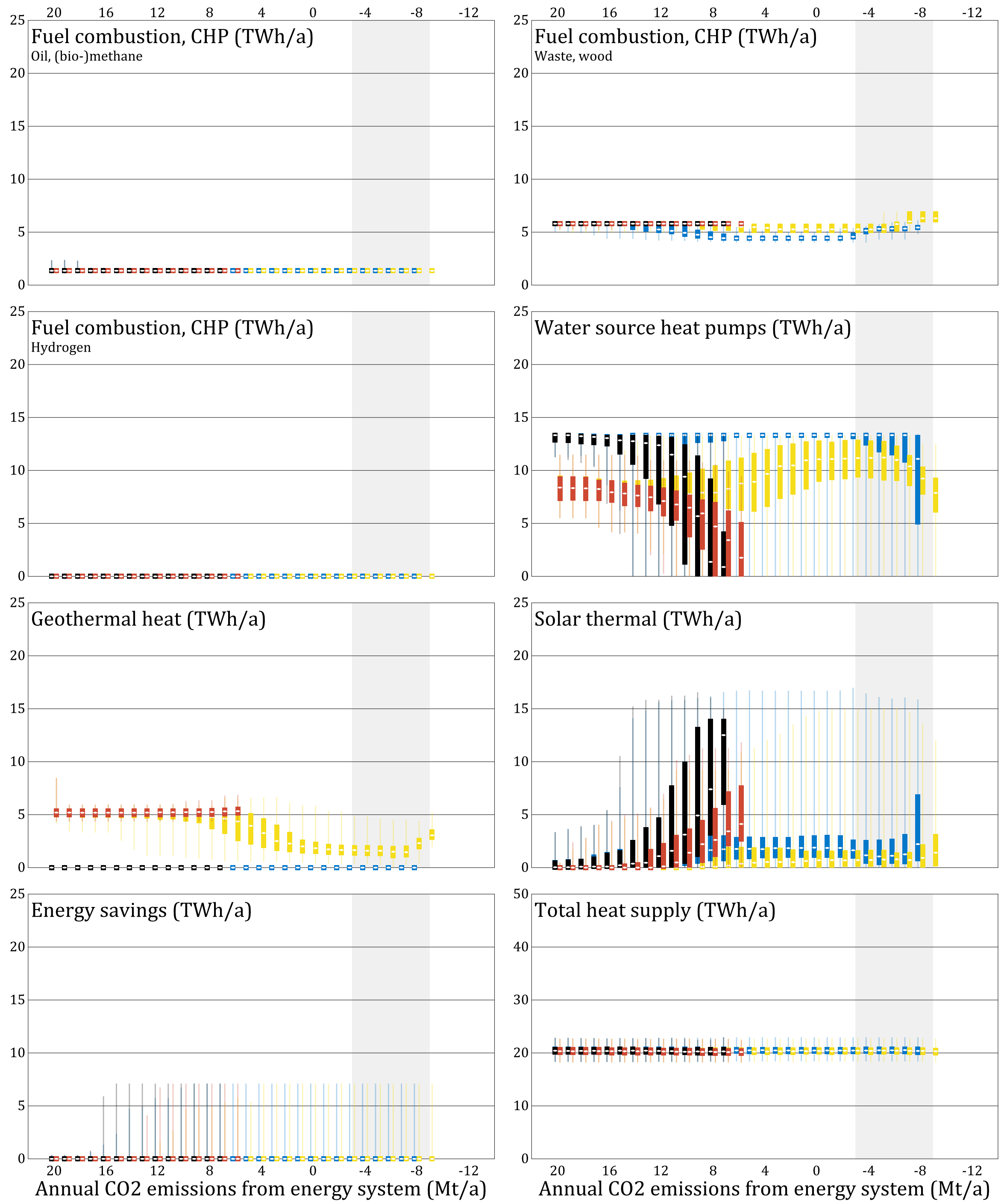


Figure 3.12: Supply of space heat and domestic hot water for district heating networks in scenario variants Yesterday, Revolution, Come together and Imagine

which has additional geothermal energy available for district heating given that CCS is not a technology option. However, since we limit the total amount of geothermal energy, it is a finite resource which is saved by a combination of solar thermal collectors and a seasonal thermal energy storage. Figures 3.17 and 3.18 show the situation for single and multi family houses not connected to a heat network. The dominant technologies are heat pumps that always operate with the help of small daily thermal storage and an electric heater, both contributing to cover the peak demand and, therefore,

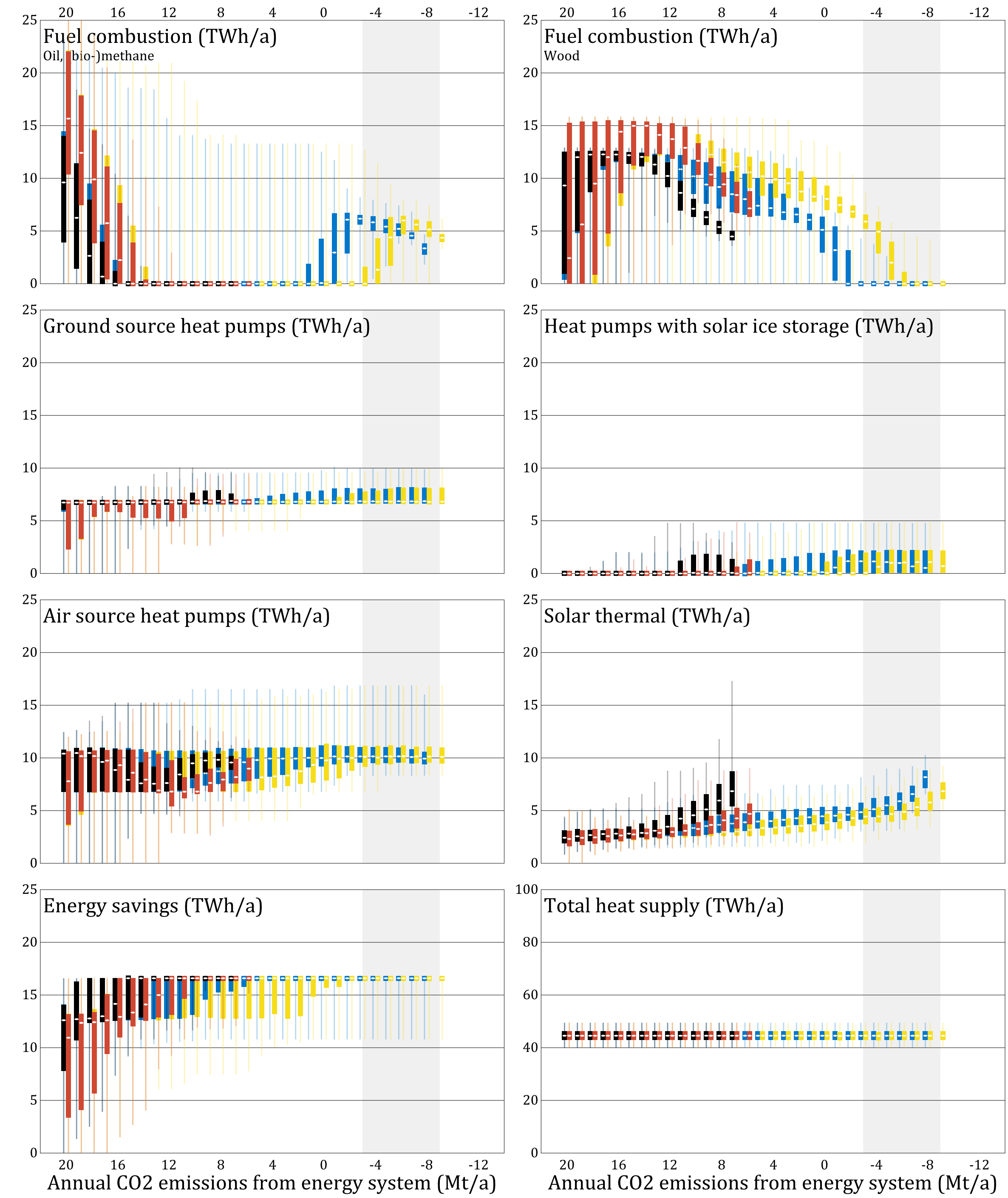


Figure 3.13: Supply of space heat and domestic hot water in single and multi family houses for scenario variants Yesterday, Revolution, Come together and Imagine

increasing the utilization rate of the heat pump. For DEC1, we also show the regeneration of the borehole field with solar thermal collectors. This allows to go beyond the limit of 5 TWh/a for not regenerated boreholes. The solar ice option in DEC3 is also chosen to a smaller degree. DEC4 and DEC6 use gas and wood as primary energy, respectively. In both cases, solar thermal collectors are deployed to save some of the limited resource, at least in the summer months. We find that solar thermal collectors are never combined with air source heat pumps due to excess electricity availability in

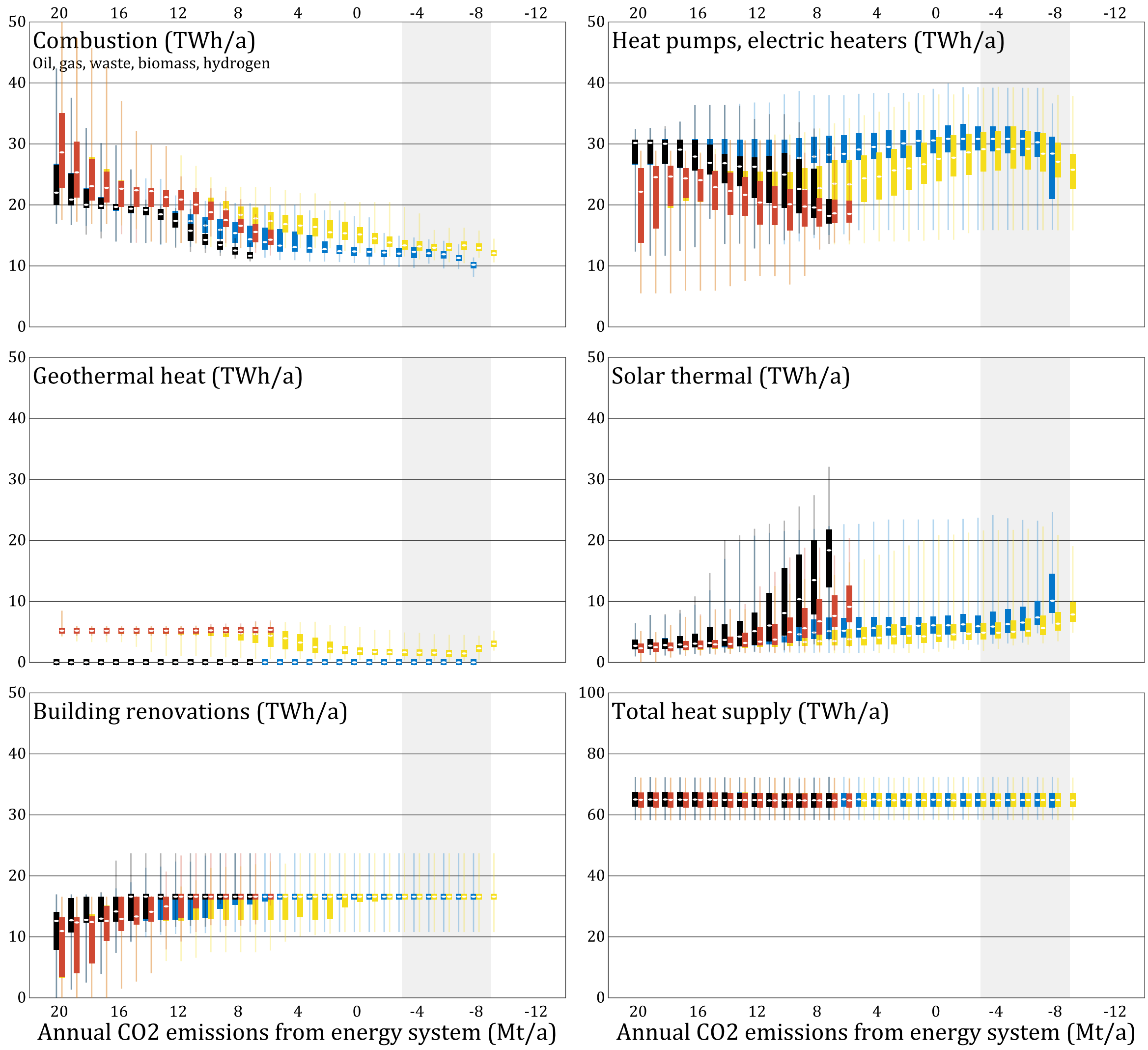


Figure 3.14: Supply of space heat and domestic hot water in scenario variants Yesterday, Revolution, Come together and Imagine

the summer (see also Section 5.4).

As in the case of process heat, these examples show how fluctuating generation by solar thermal collectors and – via heat pumps – by photovoltaics is managed by a mix of diurnal and seasonal thermal energy storage. The effect on the electricity system are considered in more detail in section 3.3.3.

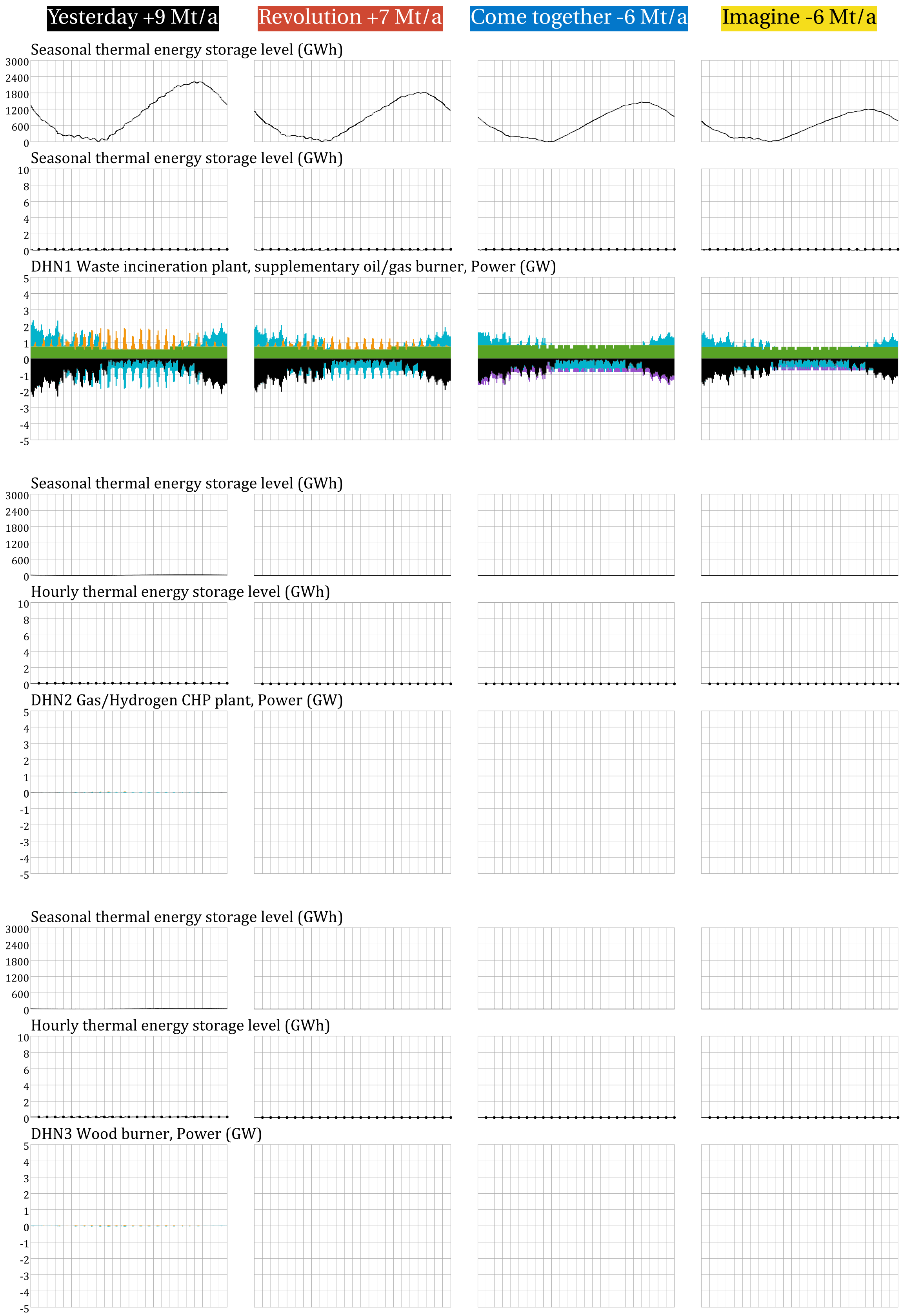


Figure 3.15: Supply of space heat and DHW via heat networks for a typical case of the four scenario variants; archetypes DHN1 to DHN3; thermal storage, hydrogen, fossil fuel, biomass, waste, solar thermal, efficiency, demand, CO2 separation, and heat rejection

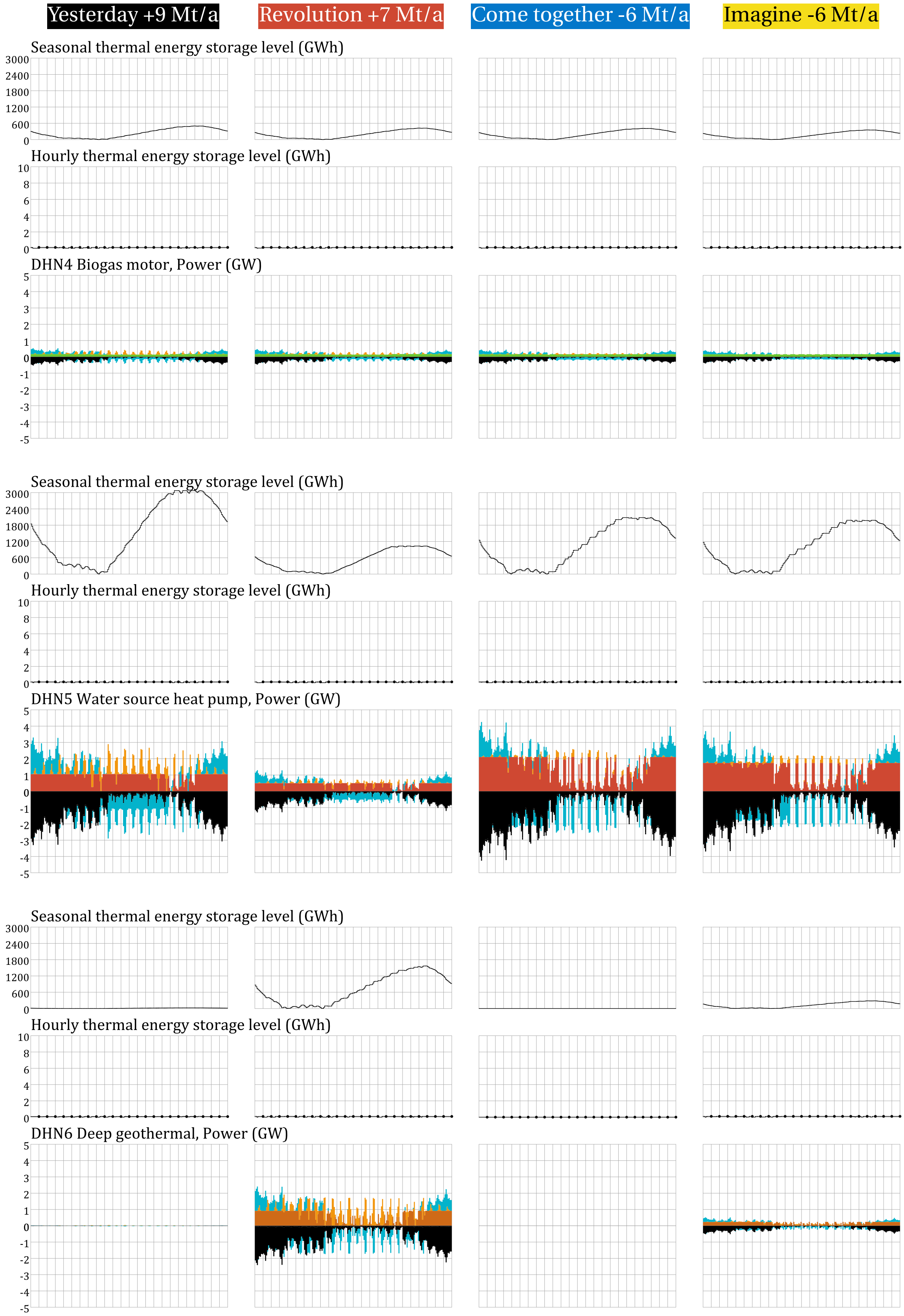


Figure 3.16: Supply of space heat and DHW via heat networks for a typical case of the four scenario variants; archetypes DHN4 to DHN6; thermal storage, heat pump, electric heater, biomass, solar thermal, geothermal, efficiency, and demand

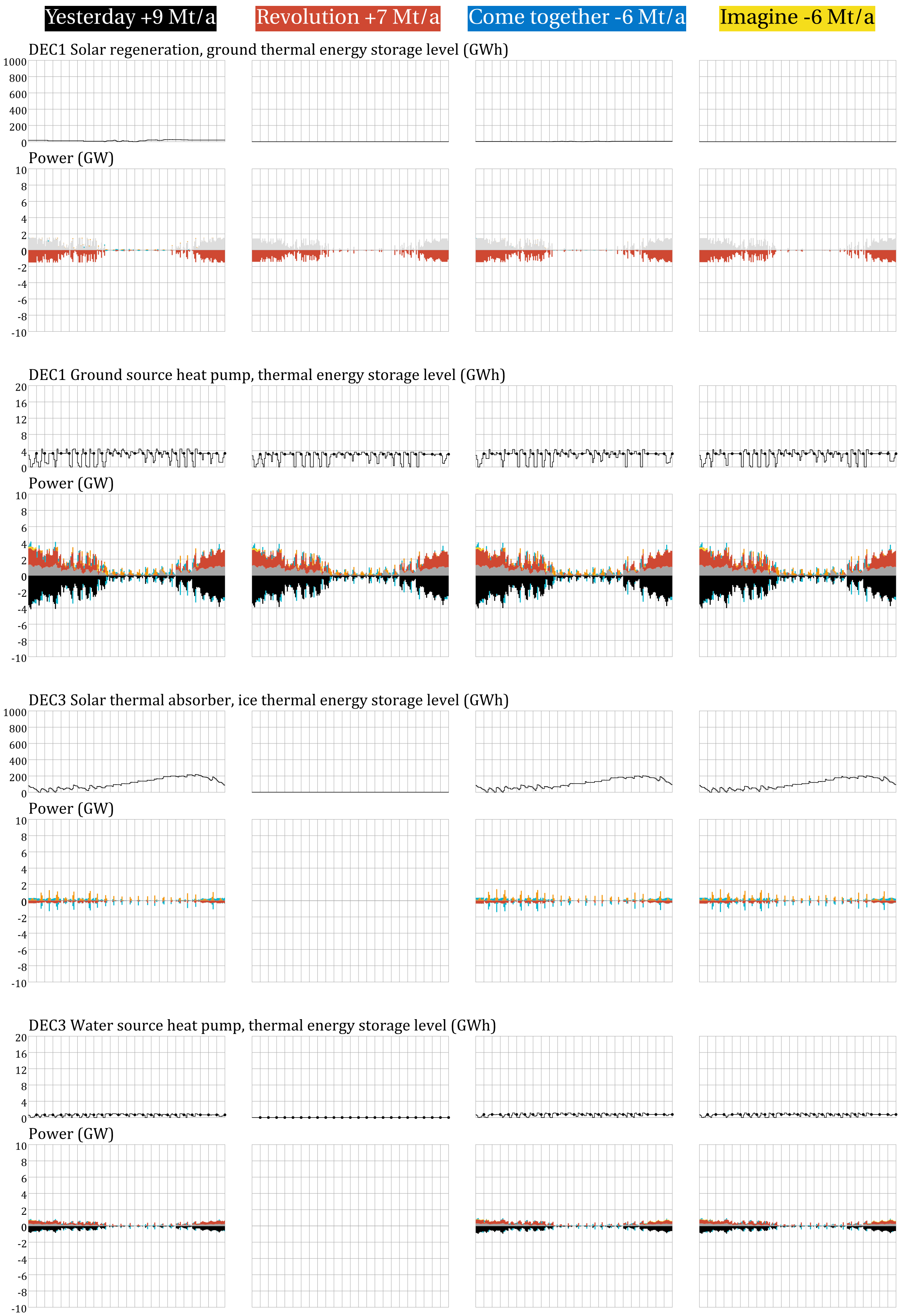


Figure 3.17: Supply of distributed space heat and DHW for a typical case of the four scenario variants; archetypes DEC1 and DEC3; anergy from ground, thermal storage, electric heater, solar thermal, heat pump, efficiency, and demand

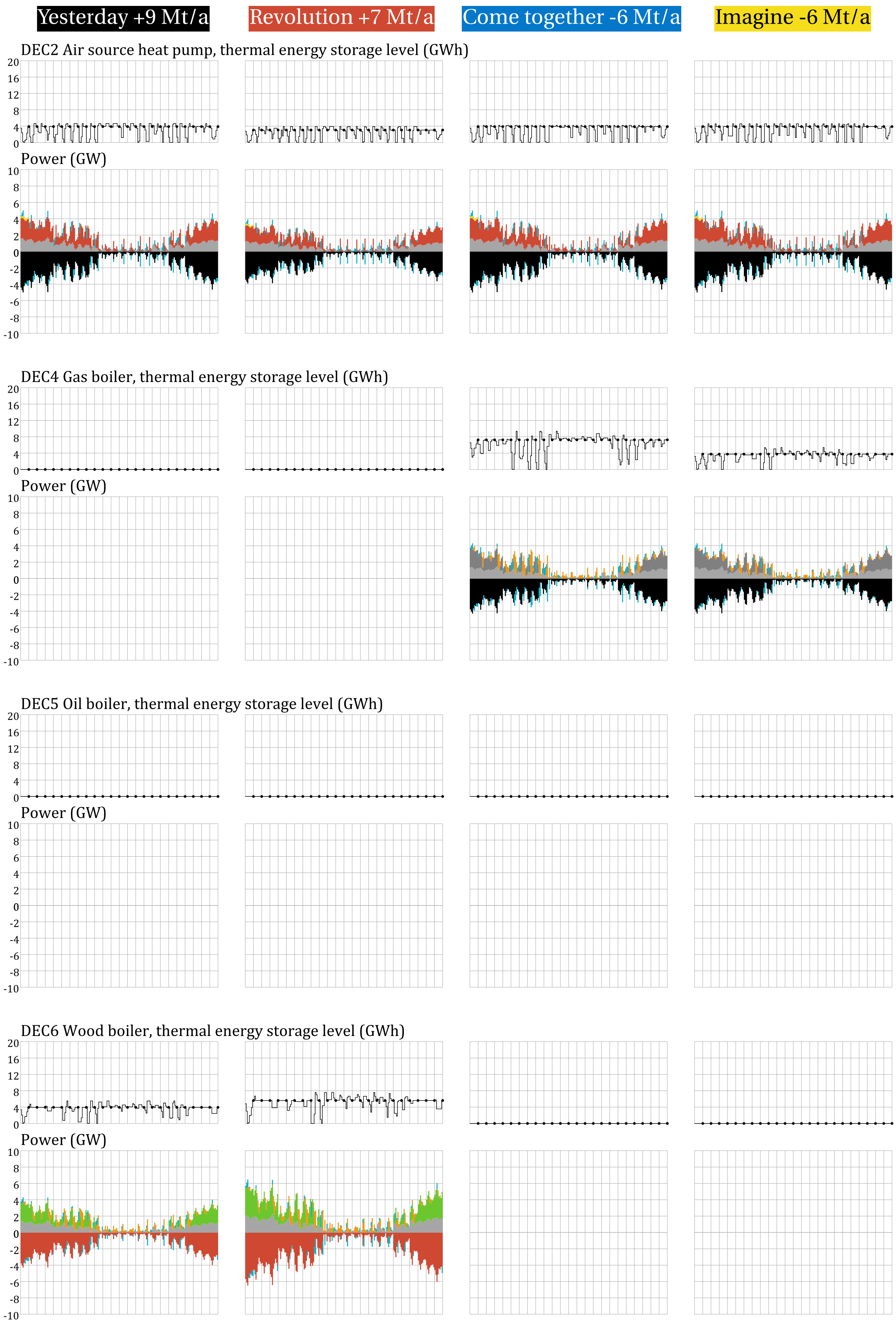


Figure 3.18: Supply of distributed space heat and DHW for a typical case of the four scenario variants; archetypes DEC2 and DEC4 to DEC6); thermal storage, fossil fuel, solar thermal, biomass, efficiency, and demand

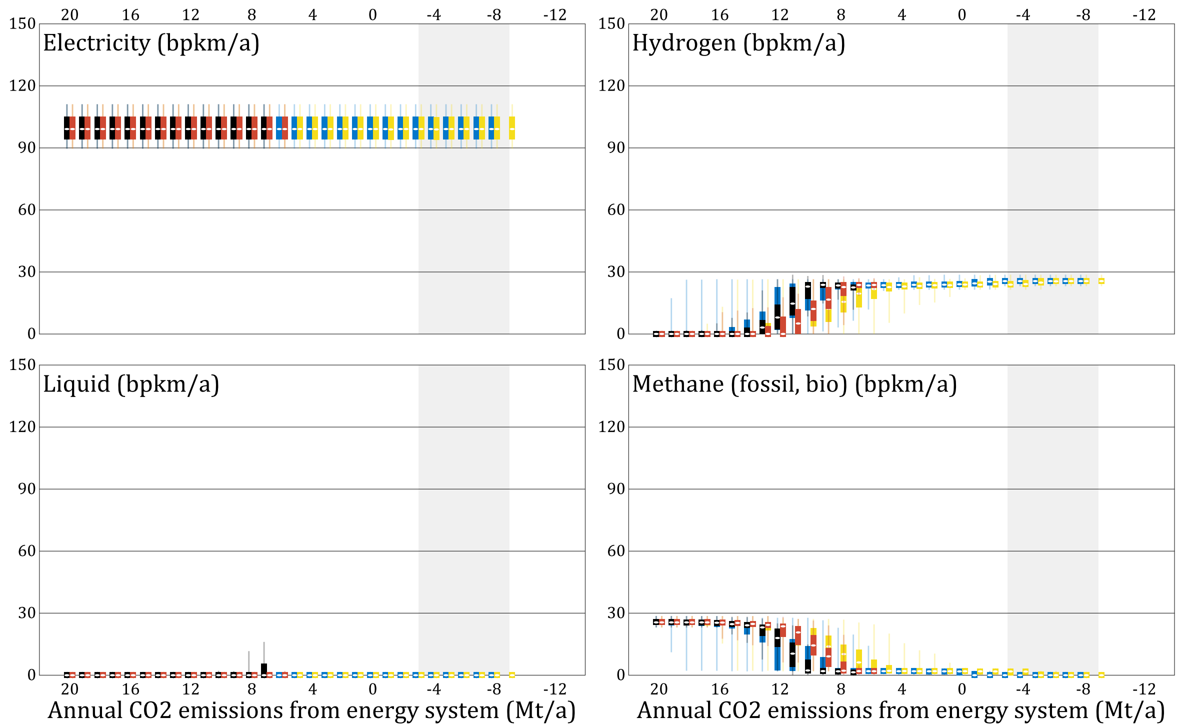


Figure 3.19: Road-based passenger mobility in person-kilometers according to the different energy carriers in scenario variants Yesterday, Revolution, Come together, and Imagine

3.2.3 Passenger and freight mobility

In SES-ETH, the demands of passenger and freight mobility are measured in terms of person- and ton-kilometers, respectively. The projections up to 2060 are based on the ARE scenarios (ARE, 2016, Marcucci et al., 2021a). We split the demands into the various basic categories (e.g. private car, bus, trains). The categories that will be most impacted by the energy transition are the private passenger cars, public buses, and road based freight mobility with heavy and light duty vehicles.

Figure 3.19 shows how the road based person-kilometer demand (private cars and public buses) is satisfied by the different energy carriers: electricity, liquid fuels, hydrogen, methane. We assume that at most 80% of the private car person-kilometers can be electric. For public buses, we assume a limit of 50%. The figure shows that electric vehicles supply indeed the bulk of the person-kilometers. For non-electric mobility, we find a gradual switch from methane to hydrogen with the increase in the stringency of the carbon target. The reason is that hydrogen can be produced with carbon-neutral or even negative emissions processes while methane will always be fossil.

Figure 3.20 shows the same split for road-based freight transport. Here we assume that at most 20% of the ton-kilometers can be realized with electric trucks. We see a similar switch from methane to hydrogen with the increase in the stringency of the target as in passenger transport. It is important to note again that these figures do not show a temporal evolution towards a future net-zero energy system, but they illustrate the optimal system for varying CO_2 targets. It is very unlikely that a methane based infrastructure will be build up for an intermediate time only to be later replaced by a hydrogen and electricity mix. Figure 3.21 summarizes the energy demand for road based passenger and freight mobility. Overall, we can conclude that in order to reach negative CO_2 emissions road based passenger and freight mobility has to switch from liquid or gaseous fossil fuels to electricity and hydrogen.

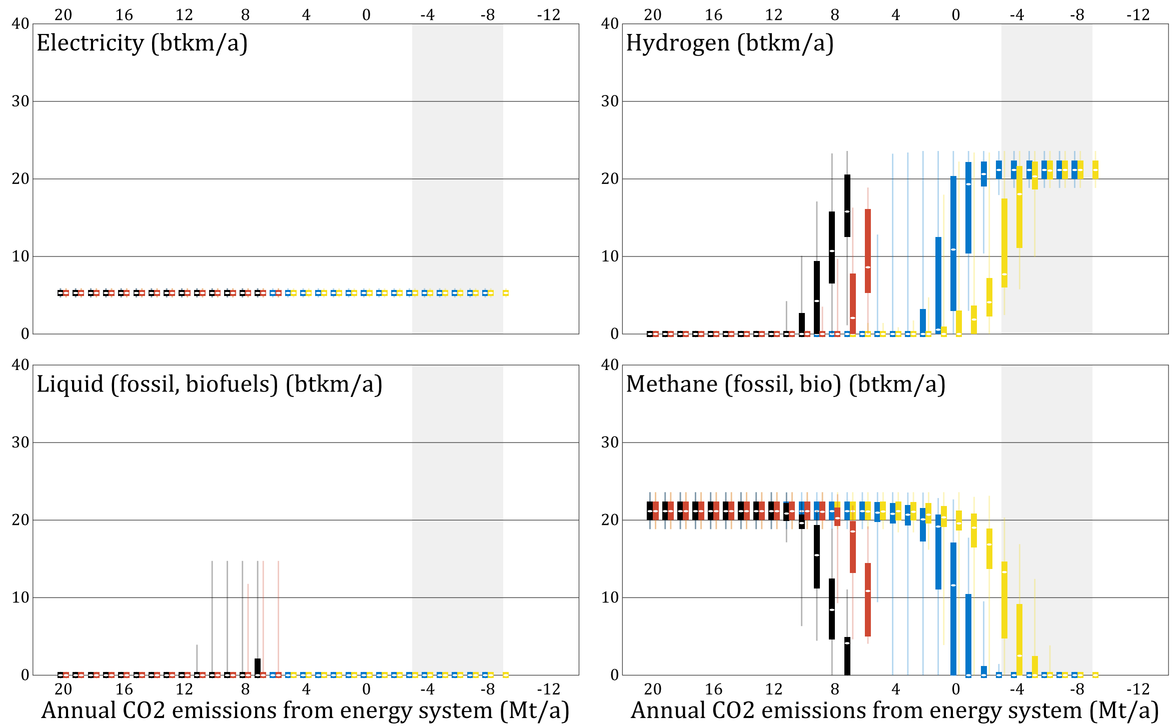


Figure 3.20: Road-based freight transport in ton-kilometer according to the different energy carriers in scenario variants Yesterday, Revolution, Come together, and Imagine

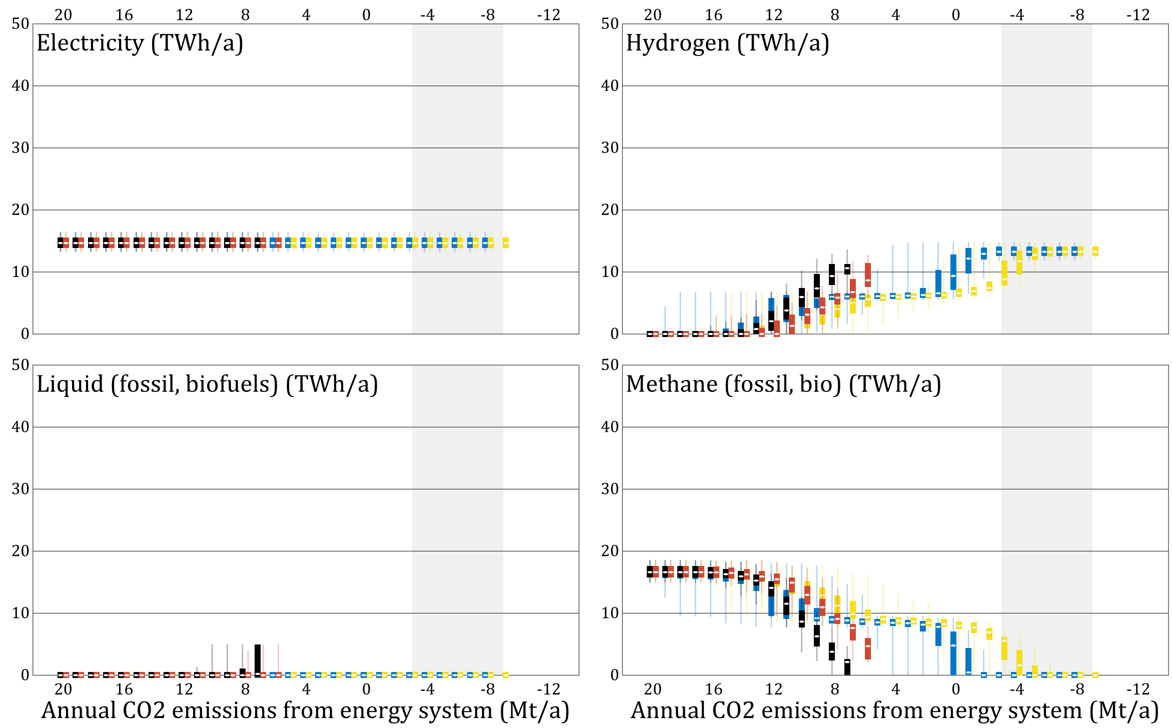


Figure 3.21: Road-based mobility as final energy demand according to the different energy carriers in scenario variants Yesterday, Revolution, Come together, and Imagine

Note that we made the conservative assumption that no biogas or liquid biofuels can be imported, due to a lack of availability. If biofuels were available they would probably go to aviation than be used on the road. Although biogas can be produced within Switzerland (Figure 3.25 on page 48), the quantities are too small to have a significant impact.

3.2.4 Recommendations for future demand streams

- Our results show a switch in the supply of process heat from methane or oil to hydrogen for the more stringent CO_2 targets, and also a growth of waste as primary energy source. A new option that comes with the strong growth of photovoltaics is the use of electrical heating in summer. We find that it should be combined with a thermal energy storage to cover the demand during the night or even the winter when a seasonal storage is available.

- For low temperature process heat, two new sources should be considered: geothermal and solar thermal energy, if needed combined with a high temperature heat pump. This option is especially interesting to satisfy the new demand for the desorption within a CO_2 separation process.

- New energy sources and a higher flexibility combined with the use of thermal energy storage will be required for the industrial sector. Applied research is needed to understand how the various sub-sectors can best cope with this change.

- We see in our results that space heat and domestic hot water will be supplied mainly with various types of heat pumps. Waste and biomass play also an important role, especially for buildings that do not allow retrofitting to heat pumps. Seasonal thermal energy storage can be used in combination with waste incineration plants and large scale heat pumps at district level. **Saving energy through building renovation is the most cost-effective option to reduce GHG emissions**.

- The roadmap for public mobility and freight transport seems clear: electricity will be the primary energy carrier up to a certain limit dictated by user preferences and economic necessities in the freight sector. Hydrogen appears as the complementary energy carrier, mostly because it can be produced in a carbon-negative way through biomass gasification with CCS (Section 3.3.1).

3.3 Intermediate streams

Electricity, hydrogen and methane have a special role in the energy system as they can be *produced* by various means and be *consumed* for various purposes.

3.3.1 Hydrogen

Hydrogen is a (potentially) clean energy carrier that will play an important role in the future energy system. We assume that it can be used for mobility, power generation, industrial heat and power, and district heating. We do not consider the use of hydrogen in single or multi family houses. A special focus is on the mobility sector that will undergo a fundamental change from gasoline and diesel to electricity. However, we assume that there are practical limits to the deployment of electric mobility, that we represent with a maximum deployment of 80% for private passenger vehicles, 50% for public transport by buses, and 20% for freight transport. The remaining person- and ton-kilometer need to be supplied by a non-electrical source, be it hydrogen, methane or any liquid fuel.

Table 3.4: Carbon footprint of hydrogen depending on the production pathway

Feedstok	**Carbon footprint**		
	Positive	**Neutral**	**Negative**
Natural gas	SMR/ATR	SMR/ATR + CCS	
Biogas		SMR/ATR	SMR/ATR + CCS
Fossil electricity	Electrolysis		
Renewable electricity		Electrolysis	
Coal	Gasification	Gasification + CCS	
Biomass		Gasification	Gasification + CCS
Import		Assumed is neutral	

Hydrogen is considered a clean fuel since it does not generate carbon dioxide emissions during its consumption. However, depending on the production process, its effective carbon footprint can vary from positive to negative. The traditional way to produce hydrogen is steam-methane reforming (SMR) of fossil natural gas. The process splits methane into hydrogen and carbon dioxide that is vented to the atmosphere. This “brown” hydrogen has obviously a positive carbon footprint. “Brown” hydrogen can be turned into “blue” hydrogen by capturing the CO_2 from the reforming process and storing it underground. The resulting hydrogen is at best carbon-neutral. When aiming at “blue” hydrogen it is useful to change the reforming process to an autothermal reforming (ATR) that inherently allows for a higher capture rate of CO_2.

The situation changes if biogas is fed to the reforming process. Such process is carbon-neutral without carbon capture and carbon-negative if CO_2 is stored underground. The same core process of gas reforming can therefore produce all flavors of hydrogen from carbon positive to negative. The same is true for gasification of a solid fuel such as coal, waste or biomass. Depending on whether the fuel is biogenic and whether CCS is applied, the resulting carbon footprint of hydrogen ranges from positive to negative.

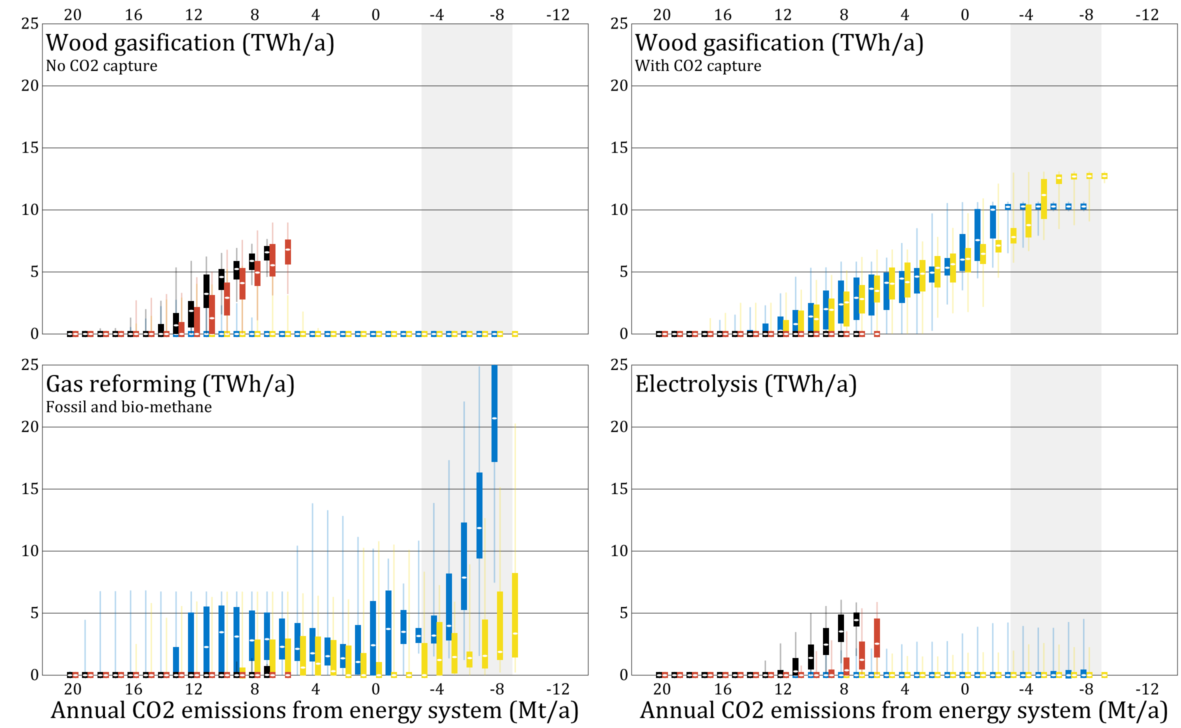


Figure 3.22: Hydrogen supply options for scenario variants Yesterday, Revolution, Come together, and Imagine

Hydrogen may also be produced through water electrolysis. Here the carbon footprint can at best be neutral when carbon-free electricity is used. The important lesson is that a carbon negative footprint - or negative emissions - can only be realized when starting from either biogas or biomass with use of carbon capture and storage. Besides being a clean vector of chemical energy, hydrogen is therefore also an enabler of negative CO_2 emissions. Table 3.4 summarizes the various options. Note that this is a purely qualitative judgement that does not replace a thorough life cycle analysis of the various production routes, as it has been done by PSI in the Elegancy project (Sintef, 2020).

Annual supply and demand

Figure 3.22 shows the situation for 2060 for the four scenario variants. Wood gasification grows for all scenario variants towards lower CO_2 targets. It is eventually higher for Imagine because of the larger availability of forest wood. This technology plays an essential role in a net-zero scenario because it enables negative emissions, by delivering biogenic CO_2 for CCS, however, it is also deployed for Yesterday and Revolution, where no CCS is available. Our results show for low CO_2 targets a substantial growth of gas reforming first for Come together, and later for Imagine. This is only to a small extent fed by biogas (Figure 3.25 on page 48), it mostly uses imported fossil methane. The large quantities are only possible due to the availability of CCS (see also Figure 4.4 on page 60), however, this part is not CO_2-negative, only CO_2-neutral.

Electrolysis is present only for the scenario variants without CCS (Yesterdayand Revolution). The reason are the differences in CO_2 intensity of the various hydrogen production pathways. When CCS is not available, methane reforming will likely be CO_2 positive, since only minor quantities of biogas are available. Electrolysis can be CO_2 neutral provided that CO_2-free electricity is available. When

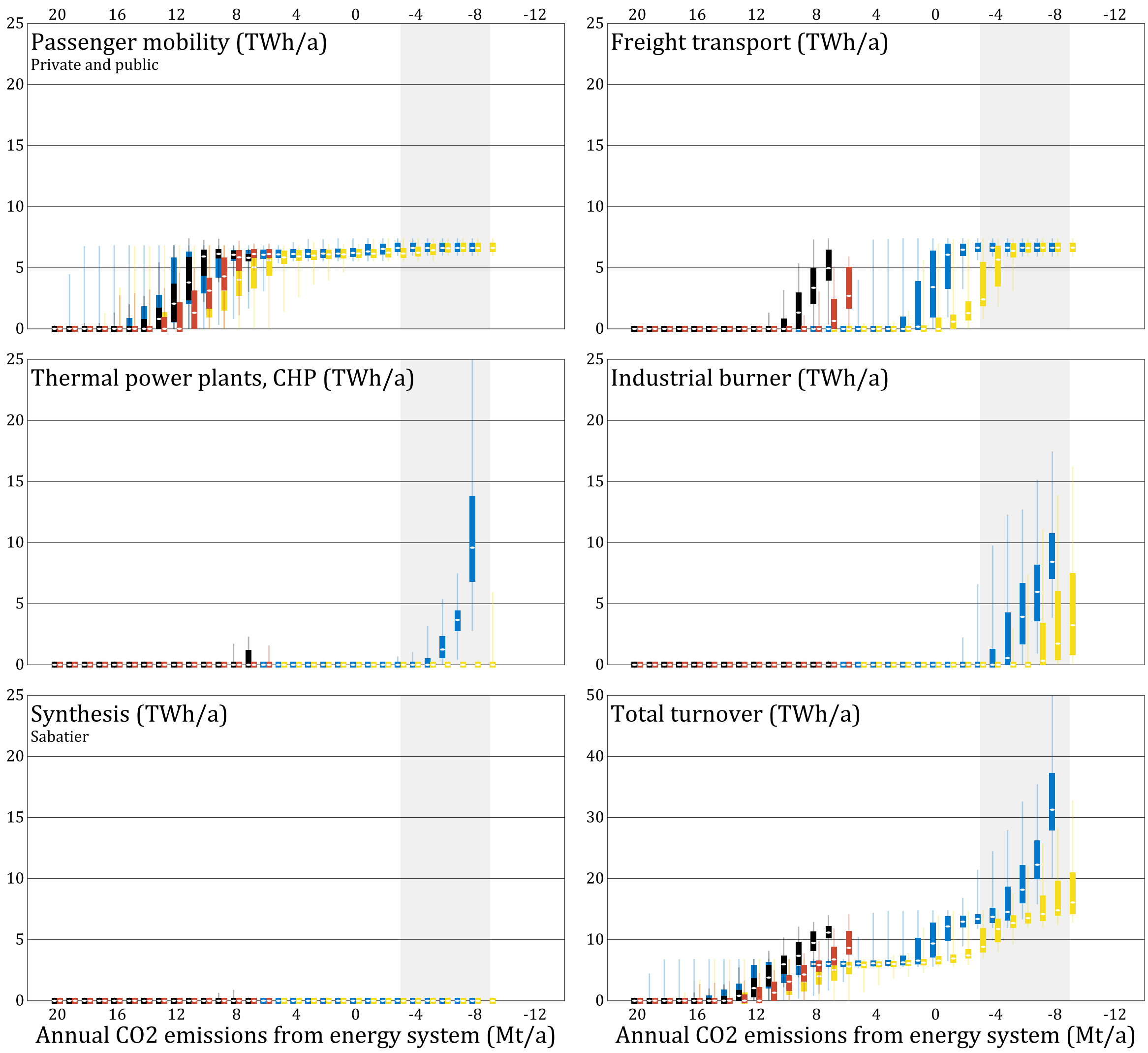


Figure 3.23: Hydrogen consumption for scenario variants Yesterday, Revolution, Come together, and Imagine

CCS is an option, gas reforming can be CO_2 neutral, as electrolysis, but with the advantage of running base load throughout the year, whereas electrolysis is best operated in summer when PV electricity is abundant.

Figure 3.23 shows the hydrogen demand. For all CO_2 targets down to approx. -4 Mt/a the usage of hydrogen is limited to freight transport and passenger mobility (private vehicles, buses). For more stringent CO_2 targets, hydrogen is used for generating power and heat, mostly in industrial processes. We find a reduction if the use of hydrogen in industry for the Imagine scenario, which is due to the availability of geothermal heat at least for low temperature processes. Comparing Figures 3.22 and 3.23 suggests that the strong growth of gas reforming is directly linked to the rise in hydrogen consumption for power and heat. Moreover, Figure 3.23 shows the total annual production that will be at least 10 TWh/a, growing up to 20–30 TWh/a for the CO_2 emissions in the range of the net-zero emissions target.

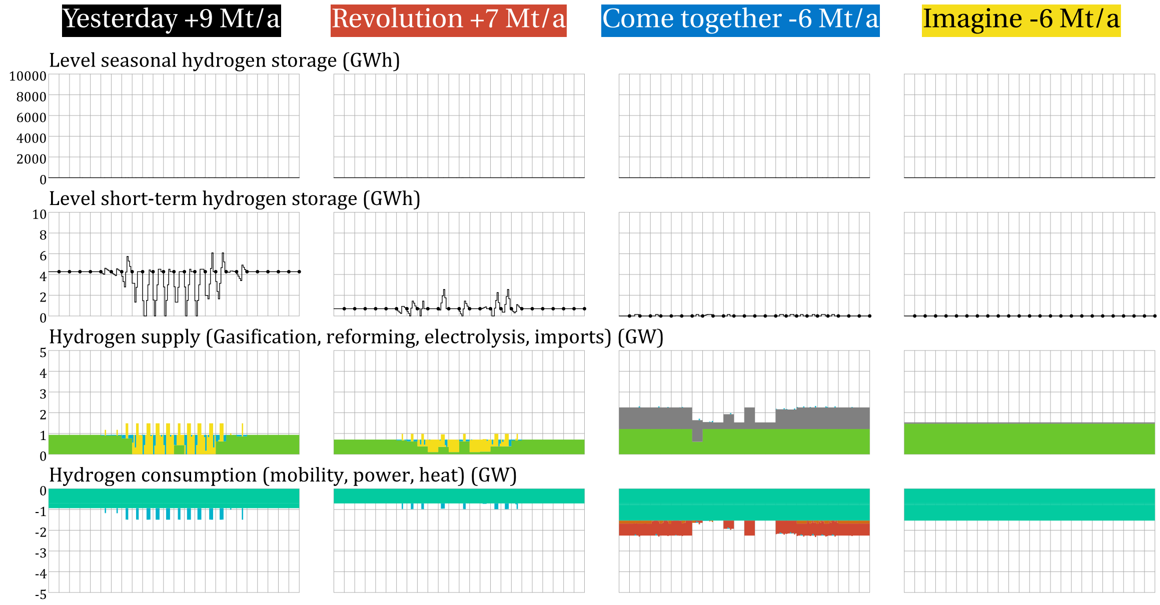


Figure 3.24: Hydrogen supply and consumption for a typical case of the four scenario variants: hydrogen storage, electrolysis, gas reforming, gasification, mobility, power, CHP, and heat

Yearly patterns

Figure 3.24 depicts the time development during the year for a representative case of the four scenario variants. On the supply side, gasification is always present. Electrolysis appears mostly for Yesterday and Revolution in summer, utilizing the peaks in PV generation. A buffer storage is used to deliver also during the night. Gas reforming appears only when CCS is available, at -6 Mt/a only for Come together. On the demand side, we find a constant use of hydrogen in mobility, and for combined heat and power plants for the Come together variant.

As explained in Section 2.1.3, we do not explicitly model hydrogen imports, instead we leave the question open to whether the technology, steam methane reforming for instance, is installed in Switzerland (importing methane and exporting CO_2), or in Norway (importing only hydrogen). Our results indicate only that hydrogen is consumed at a scale that will require steam reforming, no matter where. Wood gasification is slightly different since it uses a domestic resource, but it still requires CO_2 exports, and hence a transport infrastructure.

3.3.2 Methane

Annual supply and demand

The business of Swiss gas industry is to import and sell natural gas to domestic, commercial and industrial customers. In the past years, the amount was roughly 35 TWh. In this section focus on the supply and demand side of methane in a future net-zero energy system.

Figure 3.25 shows the situation for 2060 for the four scenario variants. For Yesterday and Revolution, in which we do not allow CCS, the imports of fossil methane gradually fades to zero. In the other variants, imports of fossil methane stay at remarkably high levels down to the lowest achievable emission targets. This illustrates that with CCS being available, a strict ban of all fossil fuel imports

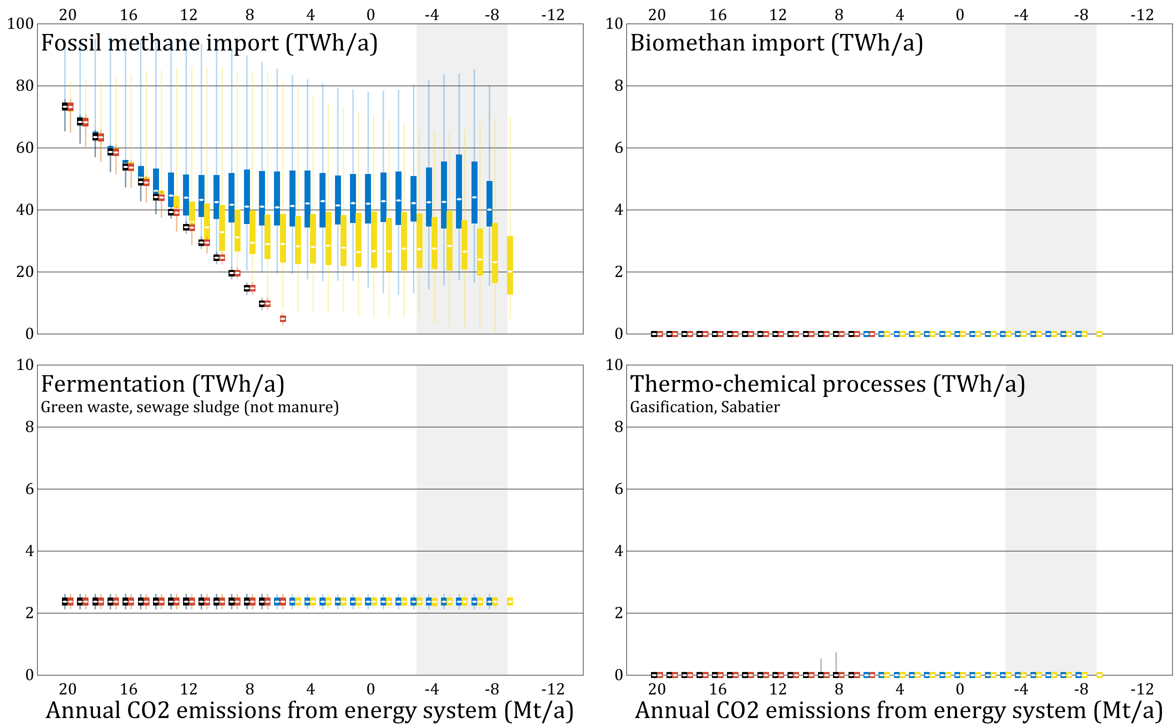


Figure 3.25: Methane supply for scenario variants Yesterday, Revolution, Come together, and Imagine

may not be the most cost effective solution.

In our scenario results, the domestic production of bio-methane by fermentation of green waste and sewage sludge is around 2 TWh/a. This is a doubling of today's production level, and it is driven by three factors: (i) an increase in the availability of green waste with population, (ii) an assumption that 80 % of green waste that is burned today in waste incinerators will be collected and available for the energy system, and (iii) a shift from composting to fermentation (today 50/50 and 10/90 in 2060) (Guidati et al., 2021a). **Nevertheless, it is clear that domestic bio-methane cannot substitute imported fossil methane**. As mentioned in Section 2.1.3, we do not consider imports of bio-methane at relevant scale.

In SES-ETH, we do model the *production* of synthetic methane through gasification and a Sabatier process (synthesis of CO_2 and hydrogen). However, these options are never chosen. The reason is the strong drive towards negative emissions: when the primary goal is to remove CO_2 from the atmosphere, producing hydrogen is more attractive than producing methane. Therefore, we find that gas reforming is the prefered alternative over the Sabatier process, which is the exact opposite. Gasification to methane produces a stream of biogenic CO_2 that would generate negative emissions, but this effect is even stronger when going to hydrogen, therefore, the methane route is not chosen.

Figure 3.26 shows the use of methane in the various sectors. Our results show that with the increase in the stringency of the CO_2 target, the use of methane for industrial and residential power and heat production gradually fades to zero. This behavior is complementary to the increase in the use of hydrogen seen in Figure 3.23 on page 46, i.e. there is a shift from methane to hydrogen. In the mobility sector, methane is heavily used for higher CO_2 emissions and fades to zero for more stringent targets (Figure 3.21 on page 41). Methane consumption stays high for gas turbine combined cycles and grows for gas reforming to supply hydrogen (Figure 3.22 on page 45). Both alternatives are possible only due

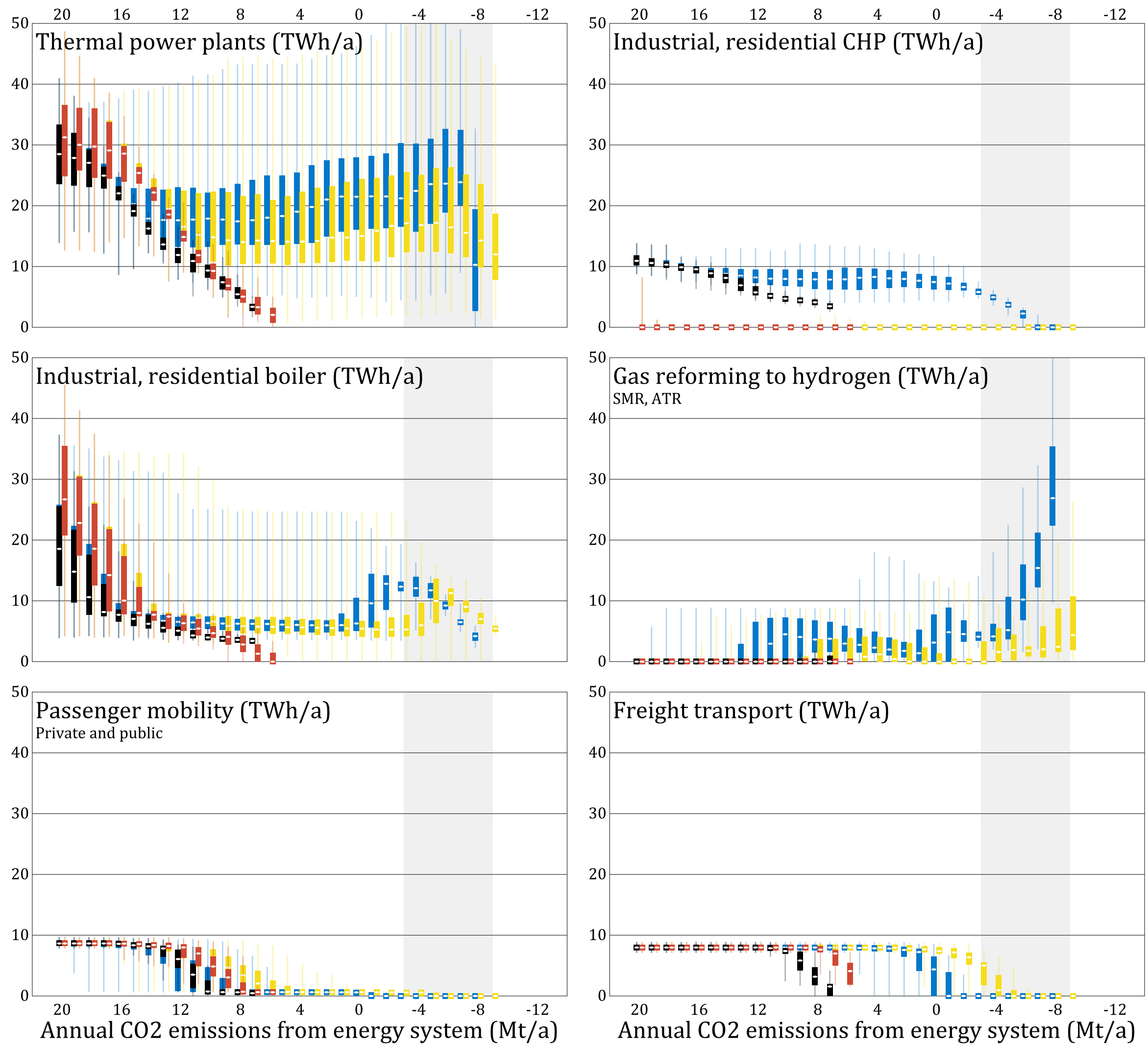


Figure 3.26: Methane consumption for scenario variants Yesterday, Revolution, Come together, Imagine

to the availability of CCS.

It is important to remind that SES-ETH is a snapshot model and does not model the transition from today's system to the future. Methane based mobility appears attractive due to the lower specific emissions compared to diesel and gasoline propelled ICVs, however, it is unlikely that a full methane fuelling infrastructure will be build only for an intermediate period of time if the final state of mobility is a mix of electricity and hydrogen.

Yearly patterns

Figure 3.27 on the following page depicts the time development during the year for representative cases of the four scenario variants. Imports are still the dominant source of methane and biogas plays only a minor role. Without CCS (Yesterday and Revolution), methane is used for power and heat, mostly in winter. When CCS is available, methane goes to gas reforming and to gas turbine combined cycles that are equipped with CCS.

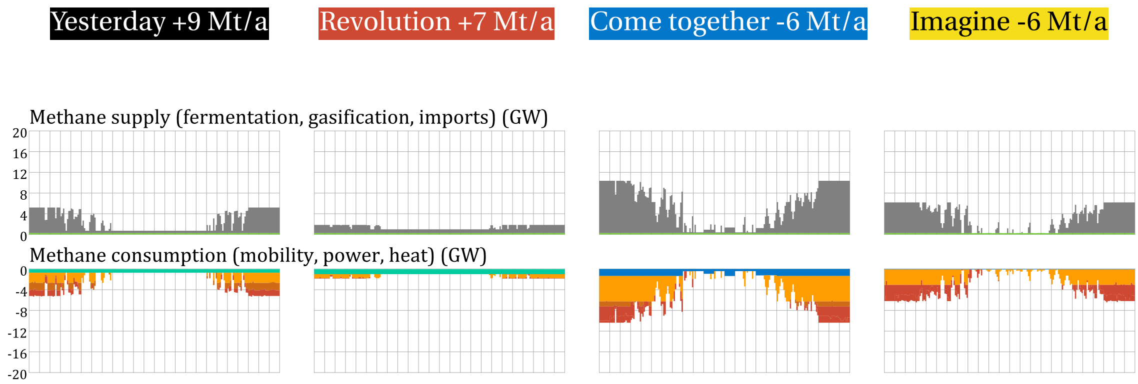


Figure 3.27: Methane supply and consumption for a typical case of the four scenario variants: imports, gasification, methanation, fermentation, mobility, gas reforming, power, CHP, and heat

3.3.3 Electricity

Switzerland faces the challenge to realize net-zero GHG emissions while replacing at the same time CO_2-free nuclear energy. The challenge is harder because the demand will most likely rise with the electrification of the heating and mobility sectors. This section highlights the key learnings from the four scenario variants for electricity production and use.

Annual supply and demand

Figure 3.28 shows the mix of supply technologies. Hydropower (regulated and run-of-river) delivers always the possible maximum for the conservative (Yesterday and Come together) and progressive (Revolution and Imagine) scenarios (Section 2.1.2).

In our results, nuclear is mostly replaced with a mix of gas fired thermal power plants and photovoltaics. The Imagine variant uses methane for the complete range of CO_2 targets, with CCS to mitigate fossil CO_2 emissions. In Come together, the results show a switch from methane to hydrogen driven power plants for the lowest CO_2 targets. New renewables are dominated by photovoltaics with wind power contributing to the maximum potential assumed in the different scenario variants (see Table 2.2b). Geothermal electricity is absent from the mix, since all geothermal heat is directly used for district heating or low-temperature industrial processes including CO_2 separation (Figure 3.3 on page 20 and Section 5.8). The figure also shows the electricity delivered by pumped hydro storage, which also appears in the consumption side. We see that the amount of pumped hydro storage is strongly correlated with photovoltaic generation.

One quantity of large interest is the total generation of electricity shown in the bottom right subfigure. Our probabilistic assessment leads to an important spread in the total electricity generation between 70 and 100 TWh/a (including the output of PHS plants). In the same way, the generation with photovoltaic has a significant spread, falling in the range of 20–30 TWh/a. This implies a growth in the production from photovoltaics of at least tenfold compared to today's level.

Figure 3.29 shows the split of the electricity demand in the different uses. Our results show that, besides the electricity demand of electric appliances (lighting, motors, etc.), the largest demands correspond to residential heat pumps (8–12 TWh/a), passenger and freight transport (17–19 TWh/a) and

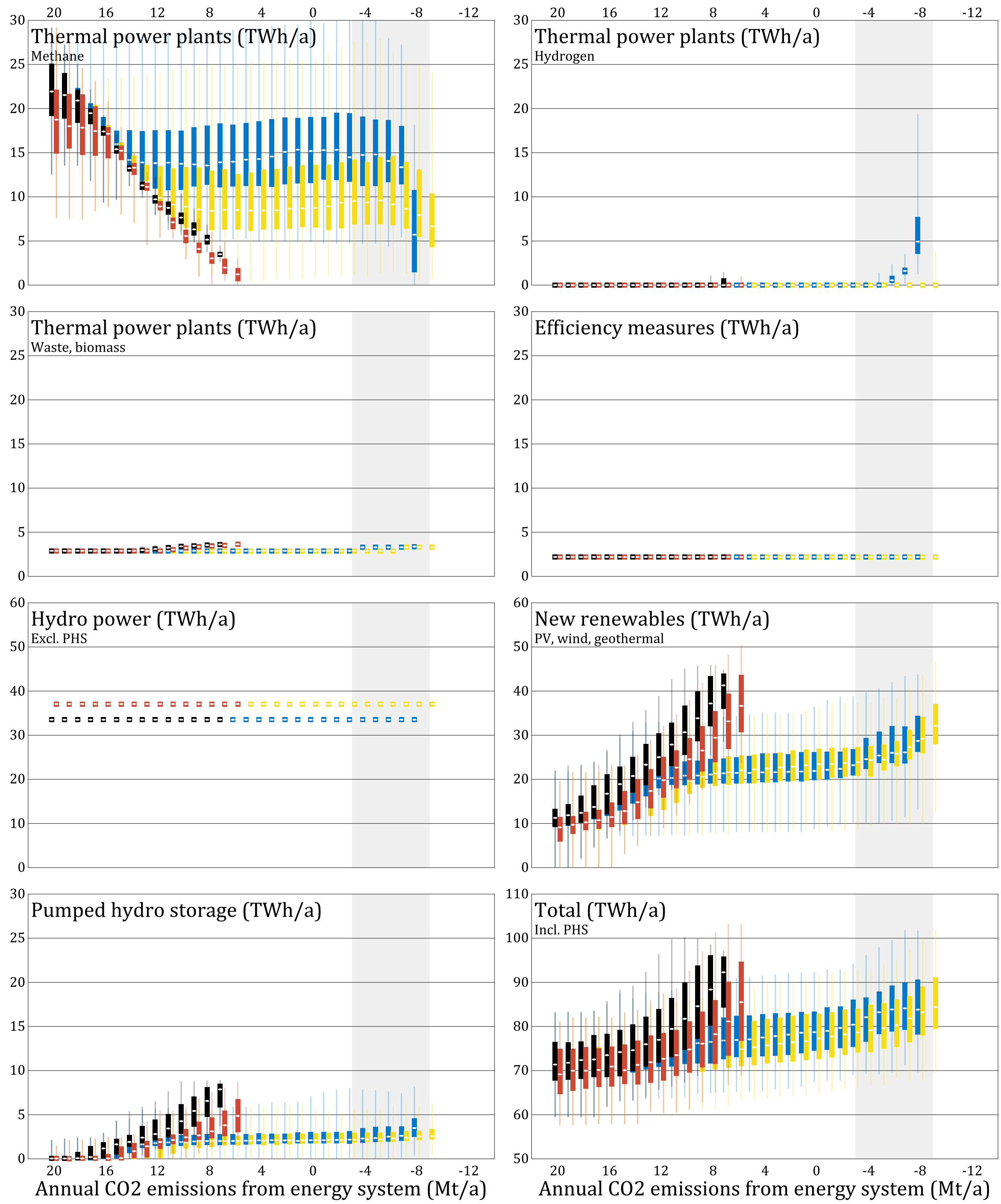


Figure 3.28: Mix of electricity supply technologies for scenario variants Yesterday, Revolution, Come together, and Imagine; hydropower is split into regulated and run-of-river, and the output of pumped hydro storage plant.

some industrial heat (3–7 TWh/a). As seen in the section on hydrogen, electrolysis plays only a small role, and appears only for the non-CCS scenarios (Yesterday and Revolution).

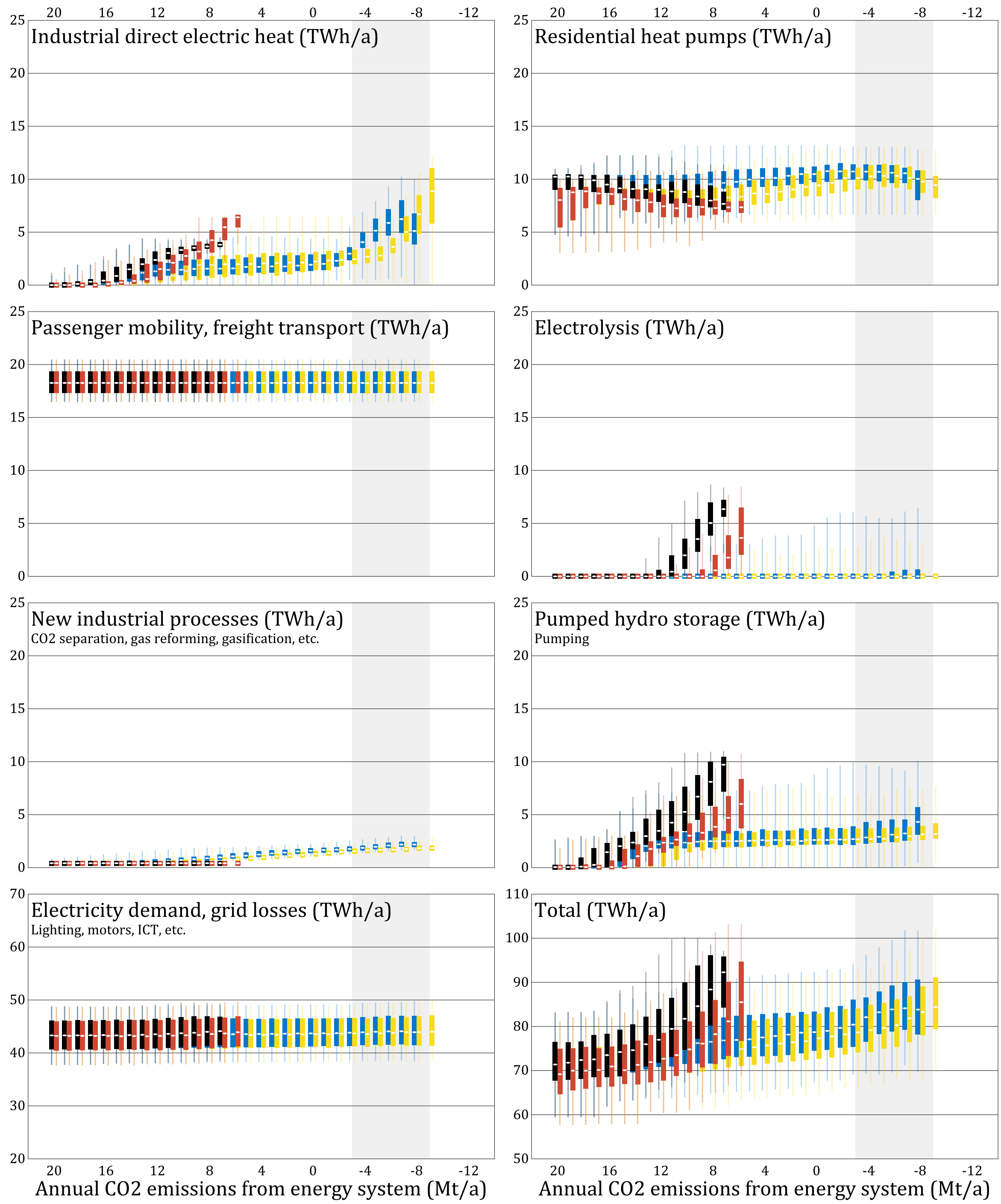


Figure 3.29: Electricity demand categories for scenario variants Yesterday, Revolution, Come together, and Imagine

Yearly patterns

Figures 3.30 and 3.31 depict the time development during the year for electricity supply and demand, respectively. The most important insight from our results is the way the system deals with the excess photovoltaic generation in summer. First of all, we find that the highest peaks are curtailed (we assume that exports in summer at noon will not be remunerated). The remaining generation is utilized

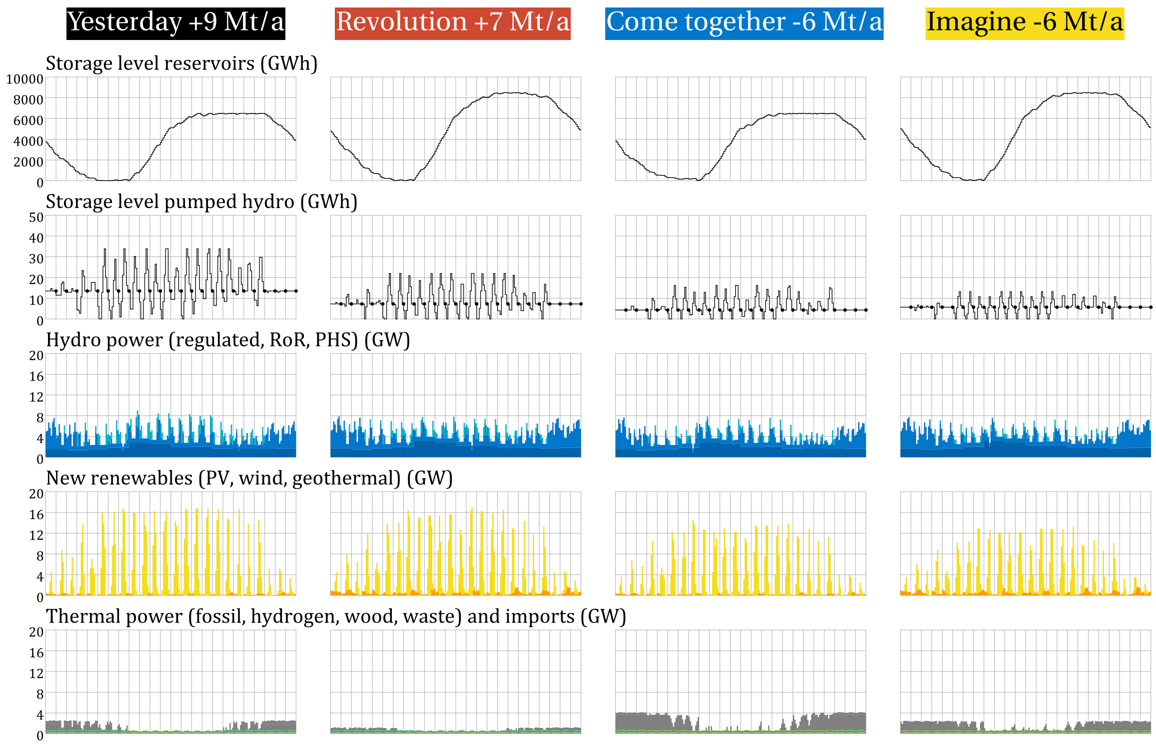


Figure 3.30: Electricity supply mix for a typical case of the four scenario variants: pumped hydro storage, hydro power, photovoltaics, wind, methane, hydrogen, biomass, and waste

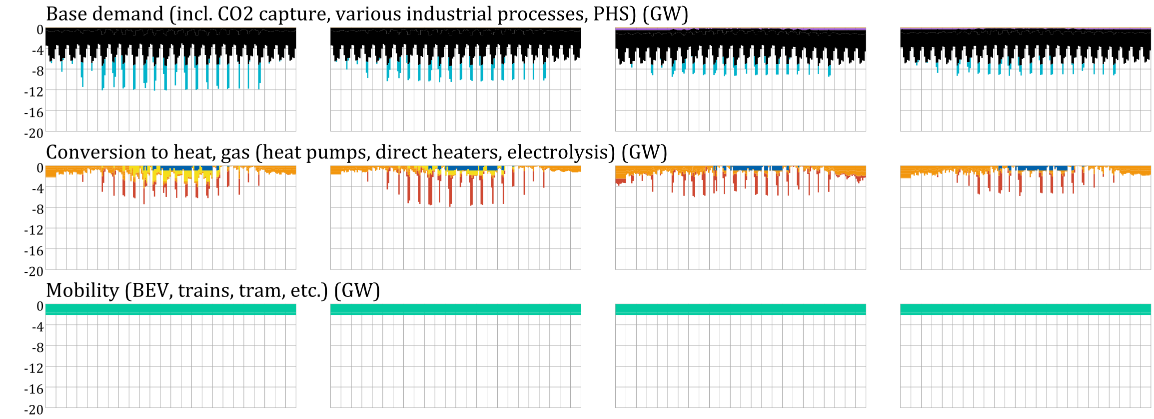


Figure 3.31: Electricity consumption for a typical case of the four scenario variants: CO2 separation, base demand, pumped hydro storage, heat pumps, electric heaters, electrolysis, and mobility

in various ways: (i) pumped hydro storage plants store the excess electricity and supply it back during the night (blue spikes in Figure 3.31); (ii) heat pumps use the electricity to charge a thermal energy storage at noon (Figure 3.16); and (iii) electric heaters supply process heat to save fuels during summer (Figure 3.9). Electrolysis appears only for the Yesterday and Revolution scenario variants (two columns on the left of Figure 3.31, see also Figure 3.24 on page 47). Electricity generation in winter is supplied by hydropower and thermal power plants fueled with hydrogen or methane (with CCS).

Besides supplying electricity storage at a daily scale, hydropower has a crucial role as flexibility provider. Figure 3.30 shows that storage hydropower plants are forced into a cycling operation the complements the PV generation in summer. For the scenarios with the advanced technology development, in which an increase in reservoir volume is possible (Revolution and Imagine), our results show that this increase in reservoir volume is always chosen by the model to shift additional excess electricity from summer to winter.

We consider these findings interesting as they address two issues commonly discussed in the context of the energy transition: (i) how to store all the photovoltaic generation in summer, and (ii) how to cover the winter electricity gap. We find a surprisingly simple answer: photovoltaic generation is mostly stored in pumped hydropower stations to deliver electricity at night in a diurnal cycle; winter electricity comes from thermal power plants equipped with CCS. Note that we do not model the power grid in SES-ETH, so it is likely that, in reality, the role of pumped hydro storage will be shared with batteries that are installed in lower voltage grids, closer to the photovoltaic generation.

As for the case of hydrogen, we have to re-emphasise that we cannot give an insight on whether the thermal power generation in winter is realized in Switzerland or abroad. This question – that is tightly linked to the treatment of imports – is discussed in Section 5.10.

3.3.4 Recommendations for intermediate streams

- Hydrogen should be produced by gasification of biomass and waste, and by methane reforming. In order to be carbon-neutral or even negative, CCS is mandatory. In our results, electrolysis (or power-to-gas) plays only a minor role. We, therefore, recommend a shift in focus to these thermo-chemical production pathways.
- Winter electricity should come from gas-fired thermal power plants. If they are fueled by methane, CCS is mandatory. Increasing the volume of the hydro reservoirs helps to increase winter production, increasing the height of the dams is therefore an important investment.
- Photovoltaic generation should be at least ten times higher than today's level. The yearly installation rate should grow by a factor of three. Therefore, we consider mandatory to install PV on every new building.

Chapter 4

CO_2 balance

The purpose of this work is to analyze how can Switzerland reduce its GHG emissions to net-zero. Therefore, we discuss in detail in this chapter the balancing of CO_2 streams. Any physical energy stream, such as methane or biomass, carries a corresponding CO_2 stream that is released when the energy stream undergoes a chemical transformation, such as combustion. Hence, we consider four types of CO_2 streams :

- Latent CO_2, i.e. the CO_2 that is inherent to a physical energy carrier,
- CO_2 in a flue gas, i.e. a mixture of air (mostly nitrogen) and CO_2 that results normally from combustion; CO_2 in the flue gas can in principle be captured through separation;
- CO_2 that is directly released to the atmosphere and cannot be captured, for instance from a vehicle or a domestic boiler;
- Pure CO_2 that either results directly from a process such as autothermal gasification or from the separation from a flue gas.

Latent CO_2 can turn into flue gas, a pure CO_2 stream or be vented to the atmosphere. CO_2 in a flue gas can be turned into pure CO_2 by separation or it can be vented to the atmosphere. Pure CO_2 can be disposed in a CO_2 storage or be vented to the atmosphere. The most important connections are from latent CO_2 to flue gas and pure CO_2 (Table 4.1).

Table 4.1: Connection between CO_2 streams

	Flue gas	**Pure**	**Released**	**Disposed**
Latent	Combustion in power plants, waste incinerators, cement plants, and gasification/reforming	Gasification and reforming	ICE vehicles, domestic and industrial boilers	
Flue gas		CO_2 separation	Vented	
Pure			Vented	CO_2 storage

The flue gas stream is fed by four types of technologies: power plants (gas turbine combined cycles, wood, waste), municipal waste incineration plants, cement plans, and gasification / gas reforming plants. The pure CO_2 stream is directly fed by gasification and gas reforming plants, via the stream that exits the process after separation of hydrogen.

All other emitters such as road vehicles, domestic and industrial boilers, etc. release CO_2 directly to the atmosphere, i.e. we do not consider the option to apply carbon capture on small scale distributed emitters. The sources of CO_2 for Switzerland are therefore limited today to the 6 cement plants, the 30 waste incineration plants, and a yet to be defined number of gas or wood power plants, and gasification / gas reforming plants.

Figures 4.1 to 4.3 illustrate the various CO_2 streams for a representative case of the Imagine scenario variant at -6, 0 and +6 Mt/a CO_2 emissions. The latent stream is fed by biological sources that originate from the atmosphere and by fossil sources from the subsurface (including limestone, $CaCO_3$, for the cement plants). The latent stream splits into the direct release, flue gas and pure stream. Part of the flue gas is vented, the rest proceeds to the CO_2 separation. At the end of the separation, part of the CO_2 is again released (assuming a 90 % capture rate) whereas the rest is now a pure stream. The pure streams are combined and disposed in the subsurface.

It is interesting to compare the three cases. The sources of latent CO_2 on the left side of the Sankey diagrams are almost identical. Also the flue gas streams are very similar, the difference being CO_2 separation that is applied for the -6 Mt/a case. The apparent difference is the switch from combustion and transport (domestic and industrial boilers, methane driven road vehicles) to gasification. Both effects are linked. The use of wood switches from domestic boilers to gasification (see Figure 3.1a), while at the same time hydrogen that is produced by gasification displaces methane in the transport sector (see Figure 3.21). Negative emissions, i.e. the extraction of CO_2 from the atmosphere with subsequent storage, are generated in the process, especially through wood gasification but also CO_2 capture on waste and cement plants.

Figure 4.4 depicts the various CO_2 streams for the four scenario variants. It follows the same logic as the Sankey diagrams by separating CO_2 streams from/to the subsurface/atmosphere. CO_2 storage initiates from CO_2 targets below +16 Mt/a, at this point we see the differentiation of variants with CCS (Come together and Imagine) and those without CCS (Yesterday and Revolution). This illustrates the fact that reaching net-zero does not simply mean avoiding any extraction and use of fossil fuels from the subsurface, but the compensation with CO_2 capture and storage plays an important role.

Figure 4.5 shows the actual sources of CO_2 for the different scenario variants. Gas turbines, waste and cement plants, and gasification plants all produce several tons of Mt_{CO_2}/a. Gas reforming plays an important role in Come together and it is almost absent for Imagine (see also Figures 3.26 and 3.22). The left subfigure at the bottom repeats the total amount of stored CO_2, whereas the right subfigure shows that the absence of CO_2 from the pure CO_2 stream being released anymore to atmosphere.

The total amount of CO_2 stored in the target range of -4 to -8 Mt/a is around 15–20 $MtCO_2$/a. Since recent studies found that CO_2 storage potentials in Switzerland (Diamond, 2019) are low, storage alternatives must be found abroad. 20 $MtCO_2$/a for around 10 million people in Switzerland in 2060 corresponds to 2 ton CO_2 per capita. If we extrapolating this to the European Union with approx. 500 million people, we can see a need for storing one Gigaton of CO_2 per year. Estimates for the storage potential in the North Sea amount to more than 100 $GtCO_2$ (IOGP – International association of oil & gas producers, 2019). Considering a ramp-up and a stable operation after 2050/60 it is clear that **a GHG reduction strategy based on CCS has a time span of one century, making it worthwhile to invest in the necessary infrastructure**.

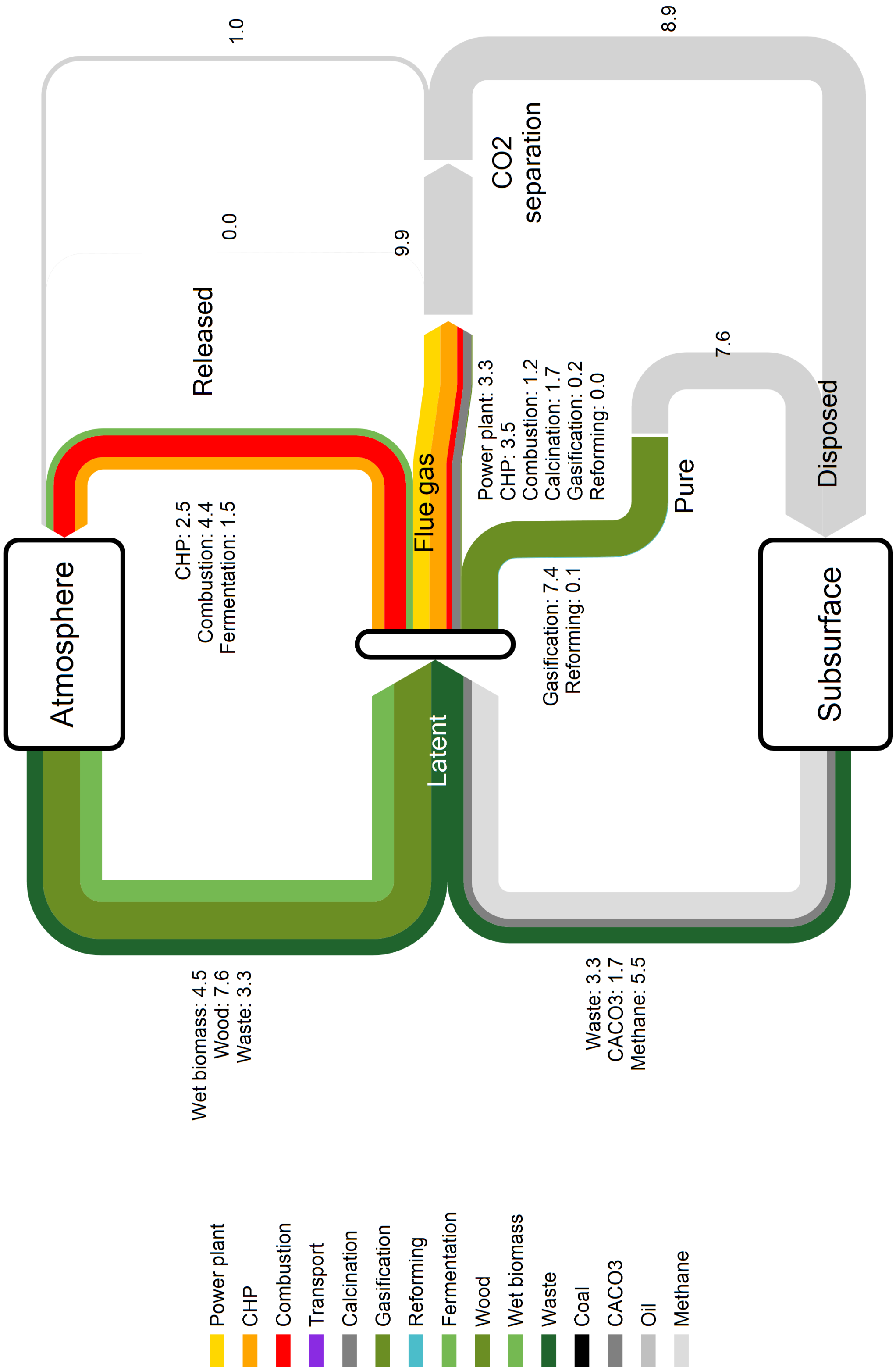


Figure 4.1: CO_2 streams for a typical case of scenario variant Imagine at -6 Mt/a

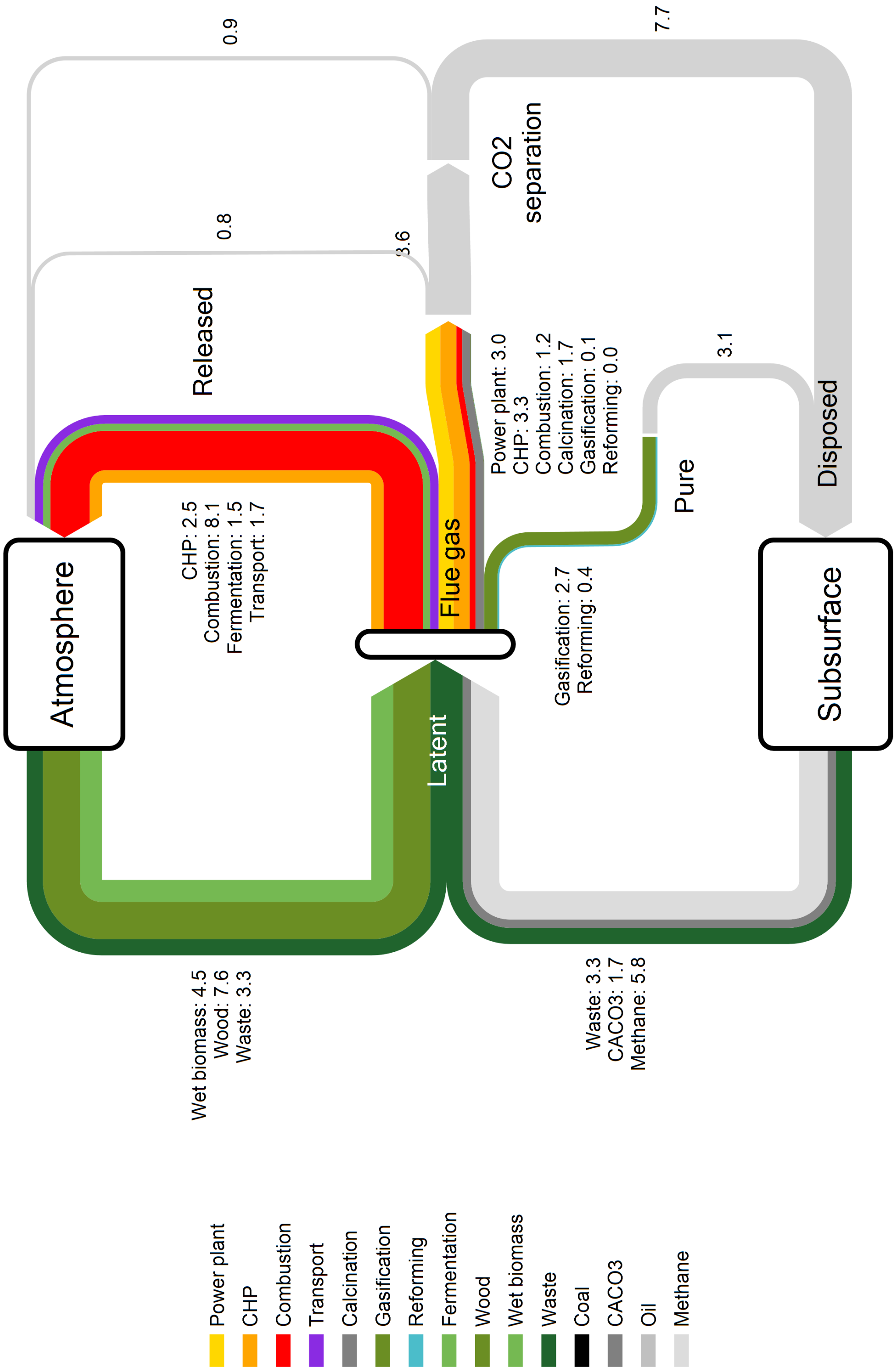


Figure 4.2: CO_2 streams for a typical case of scenario variant Imagine at 0 Mt/a

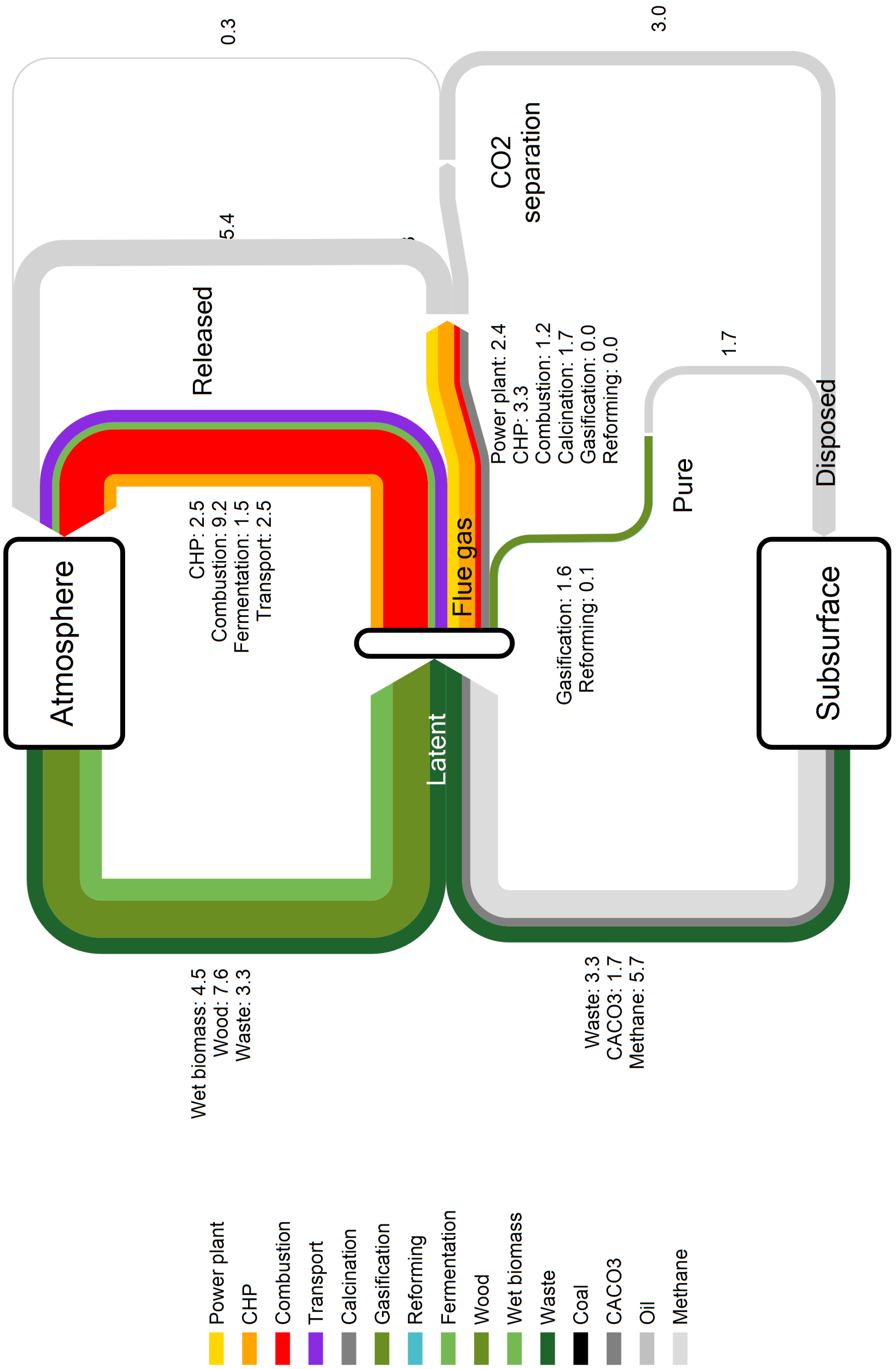


Figure 4.3: CO_2 streams for a typical case of scenario variant Imagine at +6 Mt/a

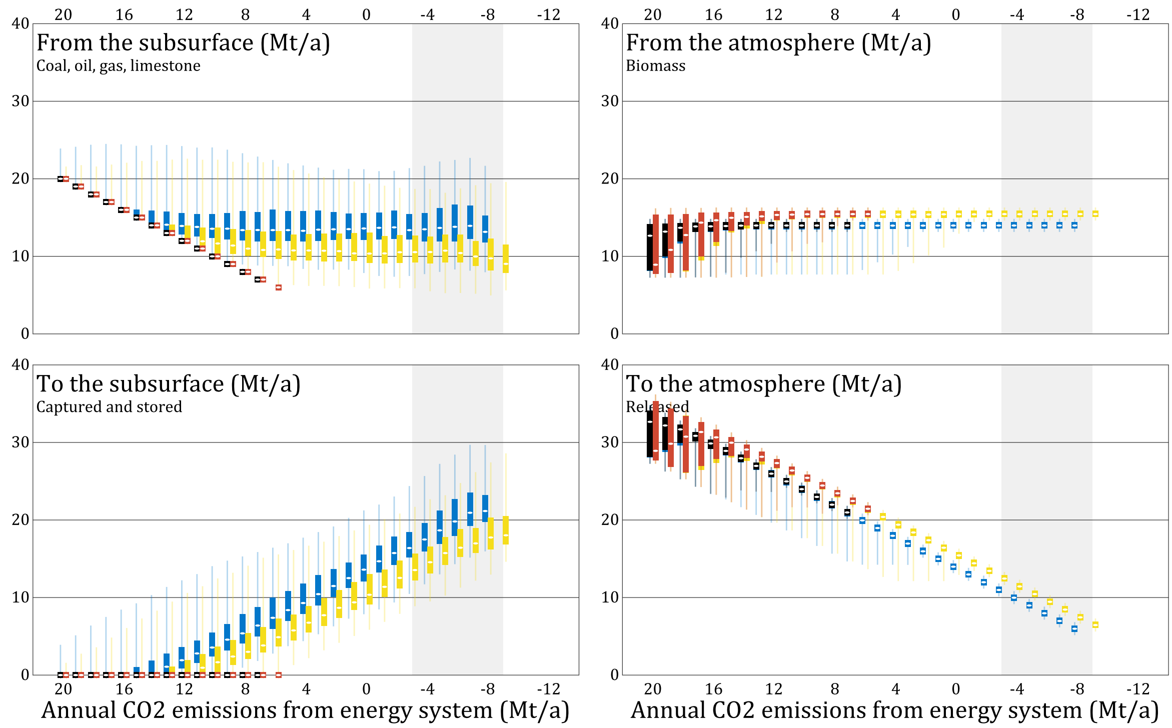


Figure 4.4: CO_2 streams between the energy system, the subsurface and the atmosphere for scenario variants Yesterday, Revolution, Come together, and Imagine

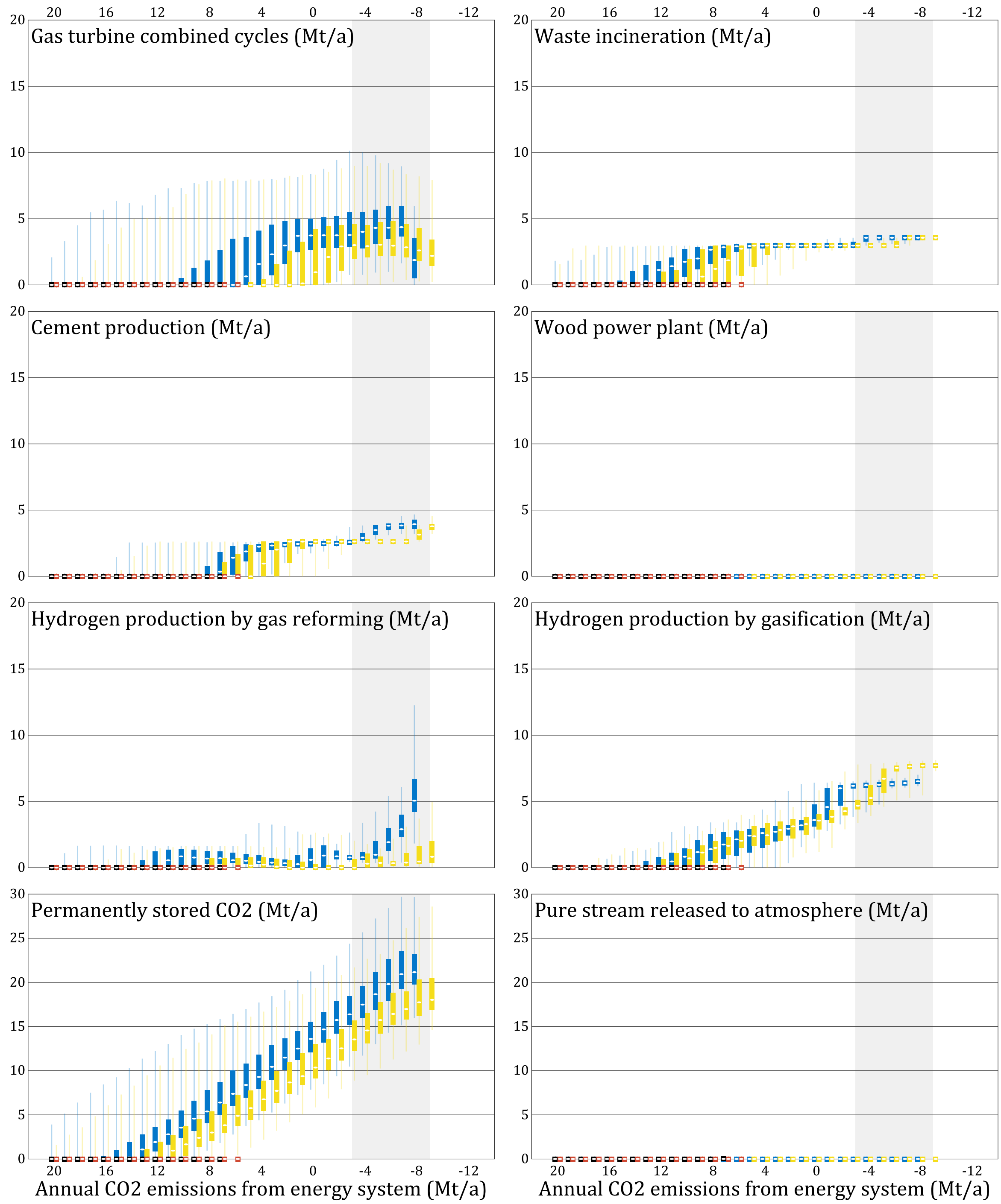


Figure 4.5: CO_2 streams for permanent geological storage for scenario variants Yesterday, Revolution, Come together, and Imagine

Chapter 5

Frequently asked questions and answers

5.1 What are the costs reaching the net-zero emissions target?

The primary objective of SES-ETH is to minimize total system costs, i.e. the sum of annualized capital expenditures (assuming a discount rate of 2.5%), variable and fixed operation and maintenance costs, and costs for primary energy, e.g. biomass or imported methane. As for every optimization problem, we can also evaluate marginal costs of every constraint in the model, i.e. the extra costs (or savings) that result from relaxing the constraint.

Figure 5.1 shows the total annual system costs and the marginal CO_2 costs, i.e. the extra costs to save an additional ton of CO_2, for the four scenario variants. As for any other quantity in this report, the uncertainty of the absolute numbers is significantly large given the uncertainty of the probabilistic variables. For the total system costs this uncertainty if in the order of several billion CHF. The plot shows, that for the non-CCS scenario variants, Yesterday and Revolution the system does not reach the region of negative emissions, needed to achieve overall net-zero GHGs for Switzerland. Before reaching the lowest feasible CO_2 target (around 8 $MtCO_2$/a), the marginal costs for these scenarios reaches very high levels of around 500–1200 CHF/tCO_2 and 400–500 CHF/tCO_2, for Yesterday and Revolution, respectively. In the Imagine variant, the marginal CO_2 costs stay at 200–400 CHF/tCO_2 for the target range of -4 to -8 $MtCO_2$/a. While, for the Come together variant, the marginal CO_2 price reaches up to 1200 CHF/tCO_2 in the most stringent target of -8 $MtCO_2$/a.

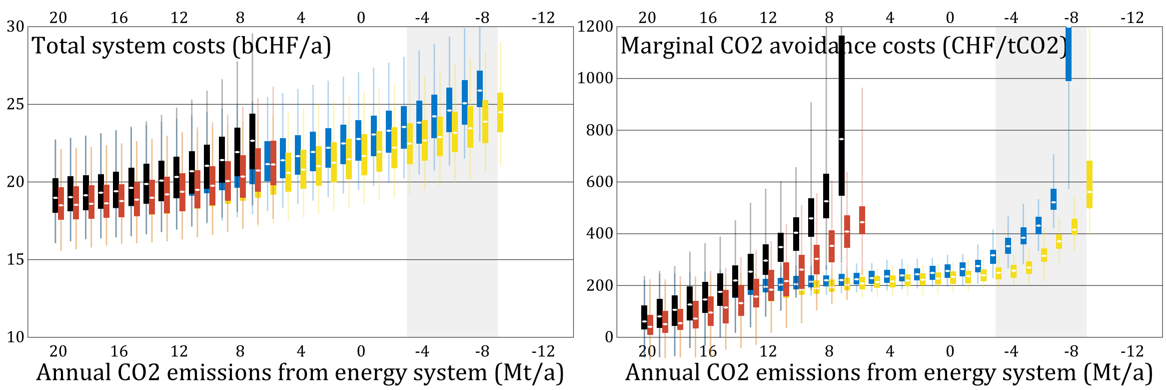


Figure 5.1: Total annual systems costs and marginal CO_2 costs for scenario variants Yesterday, Revolution, Come together, Imagine

Besides the *physical unfeasibility* to reach deep CO_2 target for those scenario variants without a market for captured carbon, one can also argue that the society has a *limit on the marginal CO_2 cost* that it is willing to pay. If we set this limit at 400 CHF/tonCO_2 – a value that is twice the maximum CO_2 price of 210 CHF/tonCO_2 that was recently proposed in the new CO_2 law (Die Bundesversammlung — Das Schweizer Parlament, 2020) –, the minimum reachable energy-related emissions for Switzerland, using our modelling results, in the non-CCS scenarios is 10–12 MtCO_2/a, which means GHG emissions of around 15–20 Mt/a. For the Come together variant, this upper limit implies emissions closer to the range of the net-zero target, and only for the Imagine variant, the Swiss net-zero emissions target can be reached. This emphasizes once more the importance of CCS.

These figures allow us to give an indicative answer to the fundamental question of how much does it cost to reduce the Swiss greenhouse gas emissions to net-zero but the analysis requires some careful interpretation. The absolute numbers include spending on fuel imports and investments in all kind of technologies ranging from domestic wood boilers to gas turbine power plants. A more meaningful interpretation is to compare the system costs in the CO_2 target zone (-8 to -4 MtCO_2/a) to a business as usual (BAU) case. In our results, we can define the BAU as those scenarios with zero marginal CO_2 costs, since this correspond to the optimal system without a CO_2 price incentive. Therefore, the increase in the total system costs to reach the net zero target compared to the BAU case is around 5–7 billion CHF/a, which corresponds to 0.5–0.7% of the GDP in 2060. It is important to notice that we do not account for the benefits of reducing greenhouse gas emissions nor the possible positive effects on the society of large infrastructure programs. Moreover, we assume a completely inelastic energy demand, which totally neglects the ability of the economic actors to avoid higher costs, for instance by purchasing smaller cars or by switching to car sharing.

> Our results show that reaching the net-zero target could lead to an increase compared to a BAU in the total system costs of 5–7 Billion CHF and to carbon prices in the order of 200–400 for the scenario with progressive technology development and high market integration.

5.2 What is the benefit of novel technologies?

From our optimization problem we can evaluate the marginal benefits of relaxing the constraints on resource or technology availability. This allow us to quantify the value of having more of a certain resource or technology. Figure 5.2 shows these marginal benefits for some aspects that change with the technology and the market integration dimensions in our scenarios definition, including: availability of wood and geothermal heat, hydropower potential and the market for captured CO_2(Table 2.2b). For instance, Figure 5.2 shows that the marginal value of having additional wood (in the emissions range of -4 to -8 Mt/a) is around 100 CHF/MWh. This means that for every additionally available MWh of wood, the total system costs decrease by 100 CHF.

First, our results show an increase in the marginal benefits with the increase in the stringency of the target, reaching the maximum value at the lowest achievable CO_2 target. This is not surprising since the more stringent the target the higher the value of having more of a certain resource. Moreover, the marginal benefits of all resources are higher in those scenario variants where the resource is scarce (Yesterday and Come together). If more of a resource is available, the marginal value of having even more decreases, a simple case of the law of diminishing marginal return.

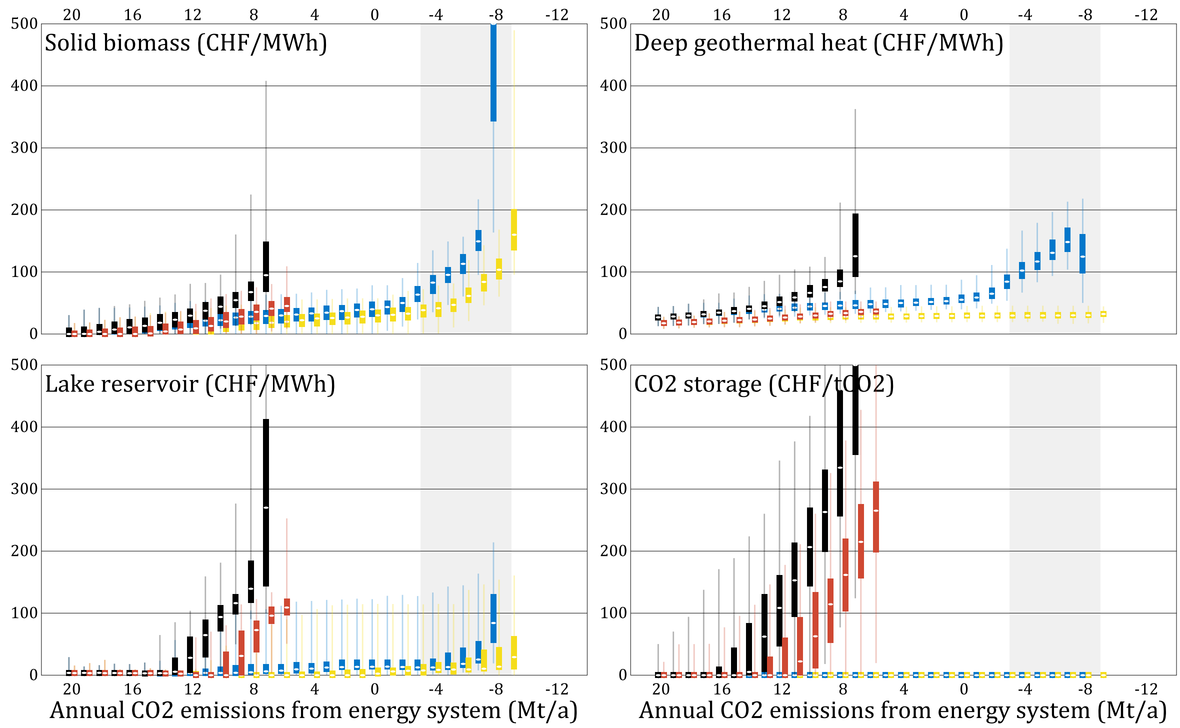


Figure 5.2: Marginal benefit of resources and technologies for scenario variants Yesterday, Revolution, Come together, Imagine

It is tempting to interpret such figures by focusing on the resource with the highest marginal values. However, one must not forget that in all cases the value is positive, i.e. increasing the resource implies a reduction in the system costs. Therefore, the question of on which technology or resource to focus should rather consider other non-monetary aspects such as the technical or social difficulty to realize certain measures. Increasing the amount of forest wood may be relatively "easy", while increasing the level of the dams on hydro reservoirs or exploiting deep geothermal energy may be more "difficult" to realize.

> We find that increasing the availability of wood and geothermal heat, hydropower potential and allowing for a high market integration of captured CO_2 could have positive effects on the realization of the Swiss net-zero target.

5.3 How does CCS impact the future energy world?

There are as many visions of the future energy system as there are researchers in the field. The purpose of this work is not to decide who is right but to distill features of future systems that are stable w.r.t. all uncertainties, and to show how certain assumptions can trigger very different energy worlds. The most fundamental assumption is the availability of CCS. The two extremes are the Revolution and Imagine scenario variants that *differ only in this respect*. Revolution features very high PV generation, fossil fuels go to zero, electrolysis is present, and the lowest achievable emission level is +7 $MtCO_2/a$ (Figures 3.28 on page 51 and 3.29 on page 52). Imagine has significantly less PV generation, uses sim-

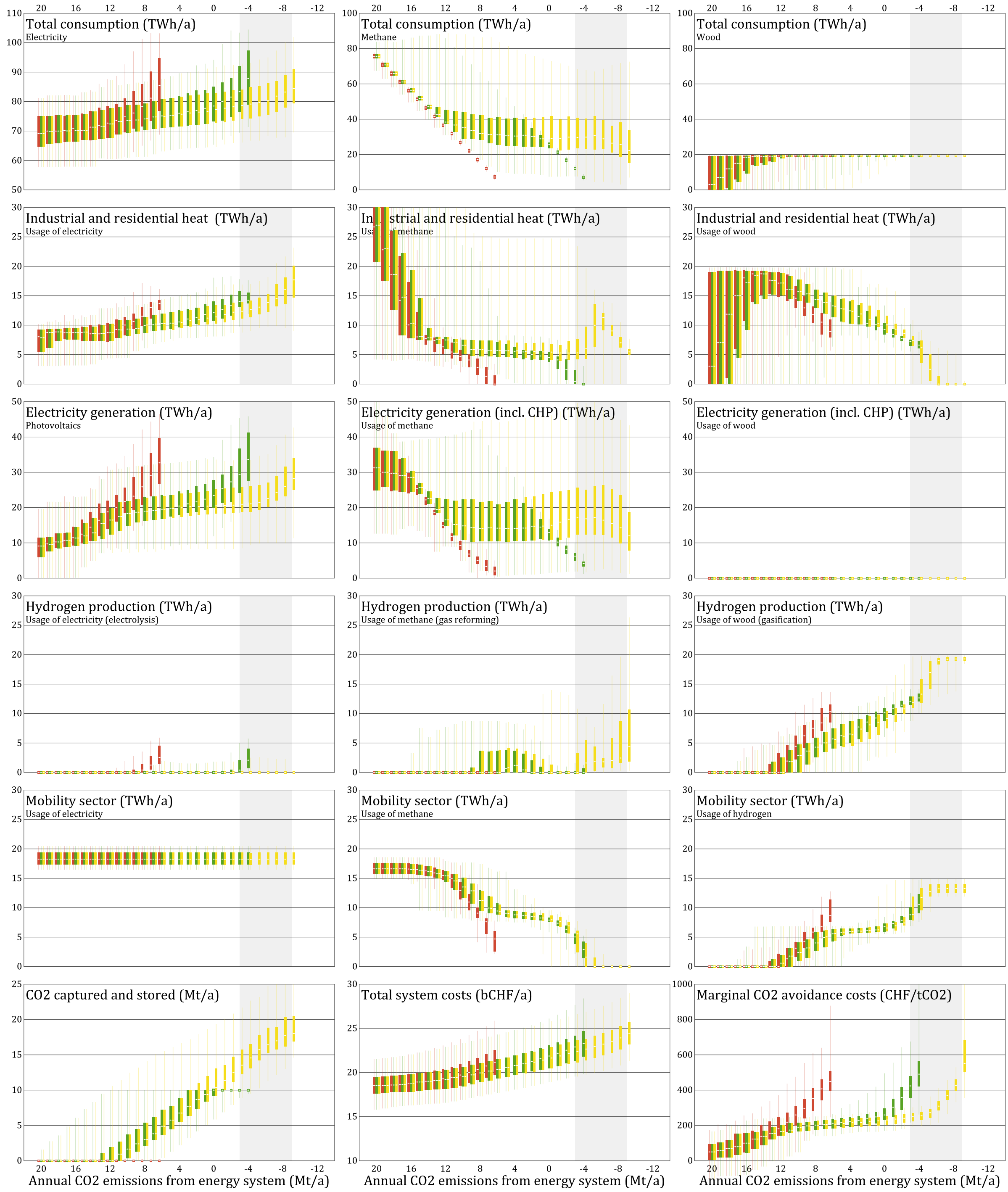


Figure 5.3: Impact of CCS availability for scenario variants Revolution, Imagine and CCS < 10 Mt/a

ilar amounts of methane as today (but now for gas turbines), has no electrolysis in the mix and the minimum emissions level is -9 $MtCO_2$/a. Revolution is close to the world that is commonly accepted as the energy future: large amounts of PV and no fossil fuels. Imagine looks like the continuation of today's system, "green-washed" by CCS.

This section studies in more detail the differences between these two worlds by performing two experiments. First, we limit the amount of stored CO_2 to 10 $MtCO_2$/a, which is half the level reached for Imagine and Come together in the CO_2 target zone of -4 to -8 Mt/a. And second, we limit the imports

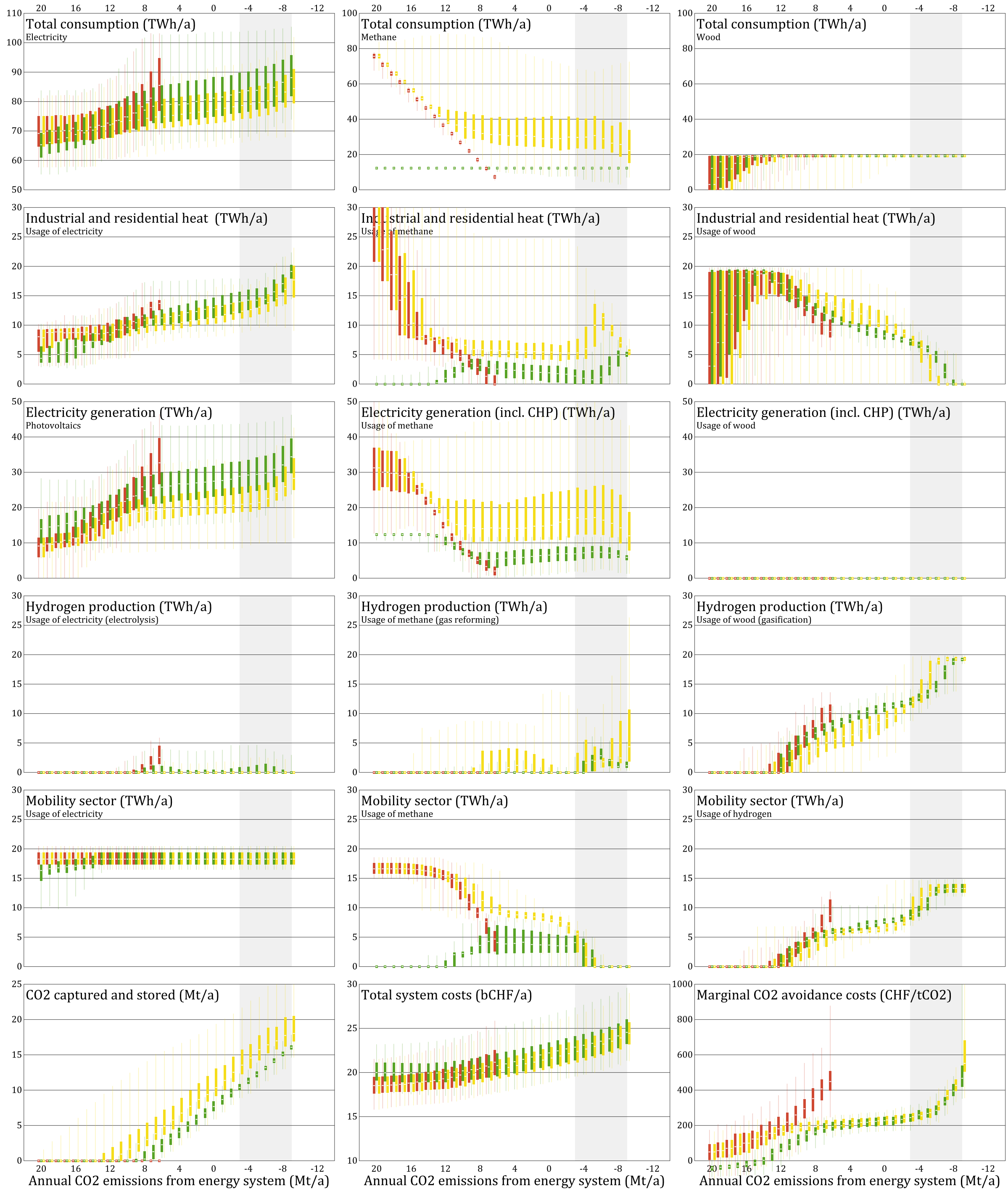


Figure 5.4: Impact of methane availability for scenario variants Revolution, Imagineand methane < 10 TWh/a

of methane to 10 TWh/a, from the 20–40 TWh/a that we obtain in the Imagine variant.

Concerning the first experiment, Figure 5.3 shows that the limit of 10 $MtCO_2$/a triggers basically an early transition to the Revolution world: PV generation and total electricity consumption grow, methane consumption decreases, and some electrolysis appears. However, also the total system and marginal CO_2 avoidance costs increase, and the lowest achievable CO_2 target increases from -9 $MtCO_2$ to -4 $MtCO_2$/a.

The first experiment proves once more the importance of CCS in reaching low CO_2 emissions. However, the second critical aspect of Imagine, given concerns regarding security of supply or resource availability, is the high consumption of fossil methane. We, therefore, cut in a second experiment the amount of available methane from the 20-40 TWh/a in Imagine to 10 TWh/a. The effect is quite different than the first experiment (Figure 5.4). Electricity generation using gas turbines reduces due to the lack of methane. This is partly compensated by a strong growth in PV generation that reaches similar levels as those in Revolution. Importantly, despite these differences in the energy system, the same deep CO_2 targets can be reached and the energy system costs grow only slightly by round 300–400 million CHF in the CO_2 net-zero emissions target range.

Admittedly, the Imagine world has a major flaw: it is not sustainable because it empties up one reservoir by extracting methane and fills up another one by storing CO_2. In this section, we showed that the first shortcoming can be partially compensated with photovoltaic generation without detrimental effects. However, the second problem can not be compensated: not having CCS will always result in higher CO_2 emissions, higher costs, and reduces significantly the chances of reaching the net-zero emissions goal. Of course, Switzerland will depend on CO_2 storage outside its borders, but – in contrast to fossil imports – this dependency is unlikely to pose any short-term threat to the country.

> An ideal energy world would need neither CCS nor fossil methane, but both options are extensively used by the Imagine scenario variant. Taking away CCS makes it impossible to reach the Swiss climate goals. Reducing methane consumption requires an increase of photovoltaic generation, but the climate goals can still be reached, albeit at higher costs.

5.4 Project SolTherm2050: What is the potential for solar thermal?

The massive growth of photovoltaic generation has overshadowed the first solar technology that became available, namely solar thermal collectors. A currently running SFOE-project addresses the question of whether or not solar thermal will play a role in the future energy system (ARAMIS - Die Forschungsdatenbank, 2019). The results documented in this report allow us to give a first answer to this question.

In SES-ETH, we model solar thermal collectors in single and multi family houses, district heating networks and low temperature industrial processes, including the separation of CO_2 from the flue gas of various emitters. As explained in Section 3.2, the heat supply in these sectors is split into various archetypes. We model the solar thermal option in all these archetypes.

Figure 3.4 on page 21 summarizes the use of solar thermal energy. We find that solar thermal energy is used in all applications, ranging from domestic heat to low temperature industrial processes. However, the its deployment is significantly higher in Come together and Yesterday scenario variants than in the Imagine and Revolution. The reason is the availability of geothermal energy in the latter variants. To verify this point, we run the Come together variant with geothermal energy and the Imagine variant without. Figure 5.5 shows that indeed the uptake of solar thermal is complementary to geothermal. Whenever geothermal is available, solar thermal is pushed down. If geothermal is not available, the deployment of solar thermal reaches levels of 10–15 TWh/a.

A word of caution is needed here: geothermal energy has the advantage to deliver reliable base load

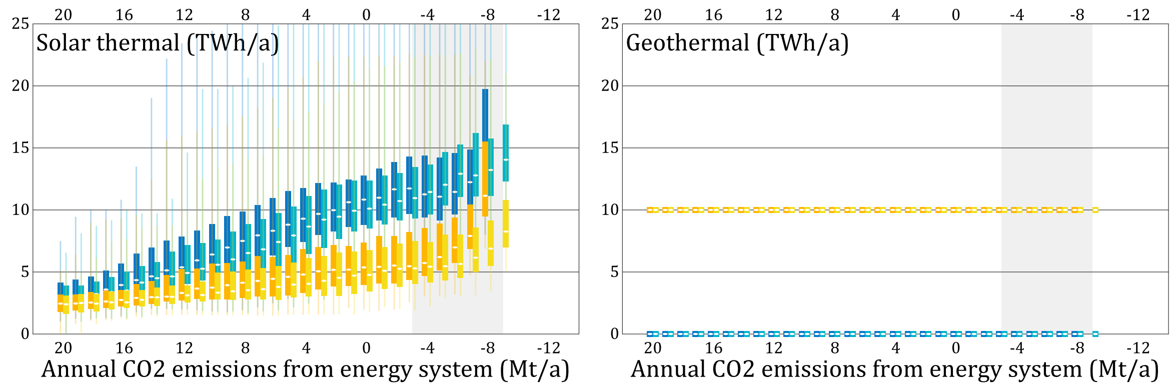


Figure 5.5: Impact of geothermal energy on the uptake of solar thermal for scenario variants Come together, Imagine *without* geothermal, Come together *with* geothermal and Imagine

heat, whereas solar thermal peaks in summer as photovoltaics and will always need to paired with a second heat source. However, solar thermal is a mature technology that exists today, whereas the large scale use of deep geothermal energy is still not routine industrial practise.

The benefit of solar thermal is that it can help saving a scarce resource. Therefore, it appears when the primary energy is gas, wood, waste or also anergy in the subsurface that is used by ground source heat pumps (Figures 3.15 to 3.18). In our results, solar thermal does not appear in connection with air source heat pumps (Figure 3.18 on page 39). The reason is that solar thermal mostly saves primary energy in summer, allowing for the storage of all the aforementioned resources that are considered inherently storable, i.e. not using them in summer automatically makes them available in winter. In the same way, an air source heat pump uses only electricity that is (i) abundant in summer due to PV generation and (ii) cannot be stored as easily as wood or ground anergy. Therefore, there is no benefit to couple an air source heat pump with solar thermal.

When we relaxed all constraints on residential heat pumps (Section 2.3), the model satisfies the complete heat demand for single and multi family houses with air source heat pumps. As a consequence, the use of solar thermal goes to zero in this field (Figure 5.6).

There is another potential link between solar thermal and heat pumps. As explained in Section 2.3, we assume a maximum availability of 5 TWh/a of free anergy for ground source heat pumps. Since these systems are especially cost effective for multi-family houses, and these are found rather in densely populated cities, it can be questioned whether 5 TWh/a are really available. We, therefore, calculated a variant where free anergy is set to zero. This restriction leaves the options of using a solar ice system or regenerating the borehole field, for instance with solar thermal collectors during summer (see also Figure 3.17 on page 38). Figure 5.7 shows that indeed the usage of solar thermal energy increases strongly under these conditions, especially for solar ice systems.

> Although solar thermal seems an "old-fashioned" technology, it could play an important role in the future energy system by delivering some 10–15 TWh/a of low to medium temperature heat for buildings and industry.

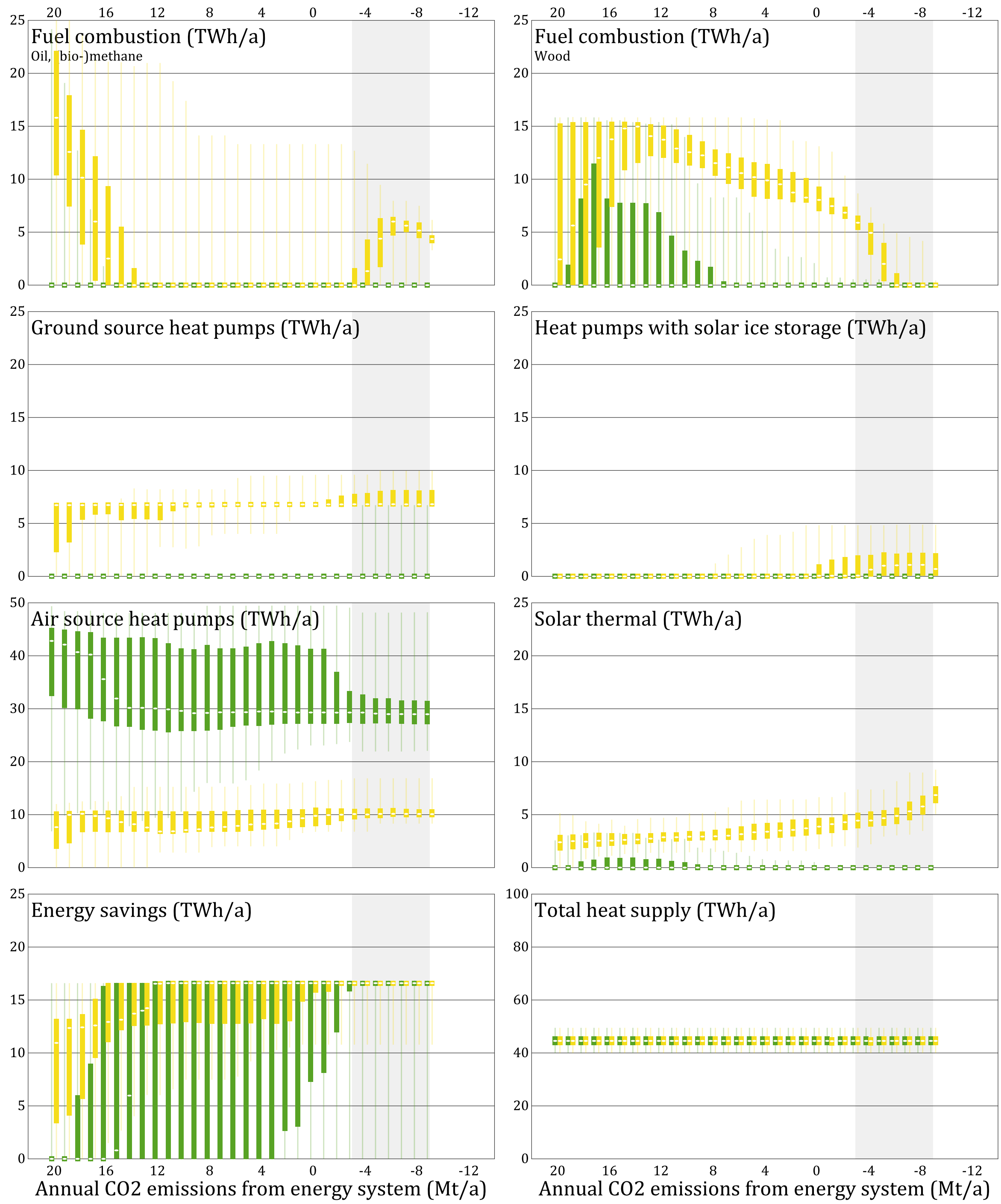


Figure 5.6: Impact of removing constraints on residential heat pumps (Section 2.3) for scenario variants Imagine and all heat pumps

5.5 Project ELEGANCY: What is the role of hydrogen and CCS?

The ACT project ELEGANCY aimed at understanding the role of hydrogen and CCS for the future energy system (Sintef, 2020). Besides a multitude of detailed technical tasks, its focus was on several country specific case studies, amongst which Switzerland. The scenario work for ELEGANCY was fully aligned with the JASM work. In this section we will summarize and interpret our scenario results

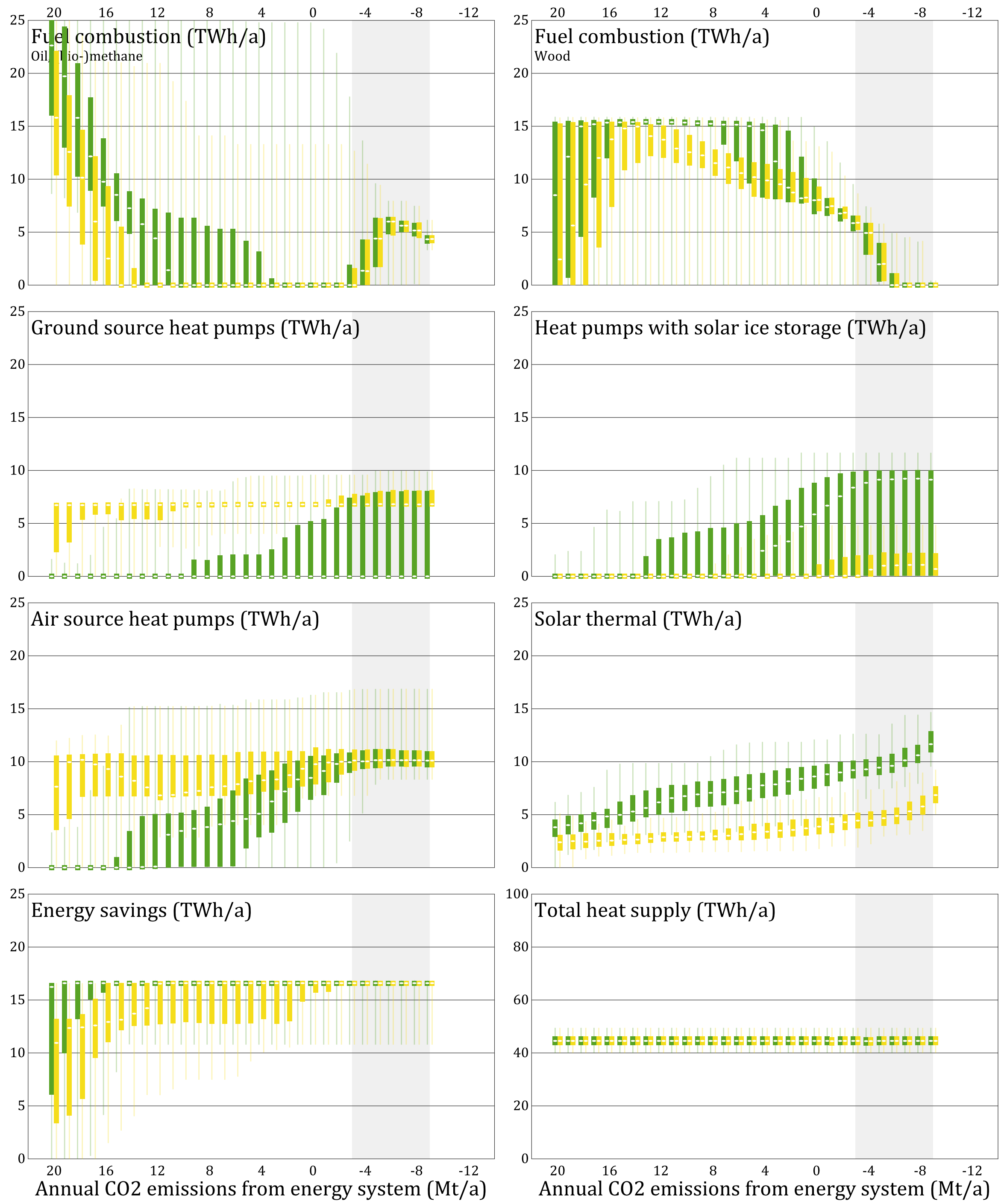


Figure 5.7: Impact of assuming 0 TWh/a of free energy for ground source heat pumps (Section 2.3) for scenario variants Imagine and full regeneration

from the perspective of ELEGANCY.

We have discussed at length throughout this report the paramount importance of CCS for reaching the Swiss climate target of net-zero emissions (Sections 5.3 and 4). We also discuss the production and usage of hydrogen in Section 3.3.1. In this section we will summarize the main insights.

- We find that reaching the Swiss climate net-zero emissions goal is not possible without CCS, and our results show that the lowest total GHG emissions would be around 10–15 Mt/a. Therefore, we find that CCS should be used in cement plants, waste incinerators, gas turbine combined cycles, and gasification and gas reforming plants that produce hydrogen (Figure 4.5 on page 61). The latter technologies were studied in detail in ELEGANCY.

- Gas reforming with CCS from imported natural gas and domestic biogas can produce carbon neutral and carbon negative hydrogen, respectively. However, the available biogas in Switzerland is limited (Figure 3.25 on page 48). Wood gasification with CCS can produce carbon negative hydrogen (Figure 3.22 on page 45), which is a key technology to realize the negative emissions that are needed to compensate for those GHG emissions that are difficult to abate (e.g. agriculture).

- Electrolysis can deliver at best carbon neutral hydrogen – when the used electricity is fully renewable. Moreover, electrolysis can only run at low capacity factors, utilizing mostly the strong photovoltaic generation in summer, whereas a gas reformer with CCS can run all year.

- Our results show a switch from electrolysis to gas reforming when including CCS as an option (compare Yesterday/Revolution with Come together/Imagine in Figure 3.22 on page 45). Only when natural gas imports are limited, electrolysis grows also for the CCS-scenarios. This is a consequence of a strong growth in photovoltaic generation that compensates the lack of methane imports (Figure 5.4 on page 66).

- In our results, hydrogen is mostly used for passenger and freight mobility (Figures 3.23 on page 46 and 3.21 on page 41). In the CO_2 target range of -4 to -8 MtCO_2/a, we also find that hydrogen is used for industrial process heat in combustion and CHP units. Note, that the use of hydrogen in transport is triggered by our assumption that at most 80% and 20% of the demand in passenger and freight mobility, respectively, can be supplied with electricity (Section 2.3). The invention of a super-battery that resolves the range and weight issues of today's technology may change this picture (Section 5.6).

> To summarize the insights from ELEGANCY: CCS is essential to reach the Swiss climate targets and wood gasification with CCS is required to deliver CO_2-negative hydrogen.

5.6 What is the impact of a super-battery for vehicles?

The analysis so far has consistently shown the strong link between hydrogen production from hydrocarbon sources (both fossil and biological) and CCS. The demand side for hydrogen is dominated by the passenger and freight transport sectors, where we assumed a maximum share in the supply with electricity of 80% and 20% of the person/ton-kilometers. What if there was a super-battery that would allow 100% electrification of all road based transport, and this the quasi-guaranteed demand for hydrogen (Figure 3.21 on page 41) disappears? Does the whole negative emissions strategy for Come together and Imagine hinge on this?

A switch to 100% e-mobility has repercussion on the whole energy system. Figure 5.8 illustrates the shifts between the various energy streams. The option to have 100% electric road mobility is completely deployed by the model, leading to an increase in electricity consumption. As a consequence,

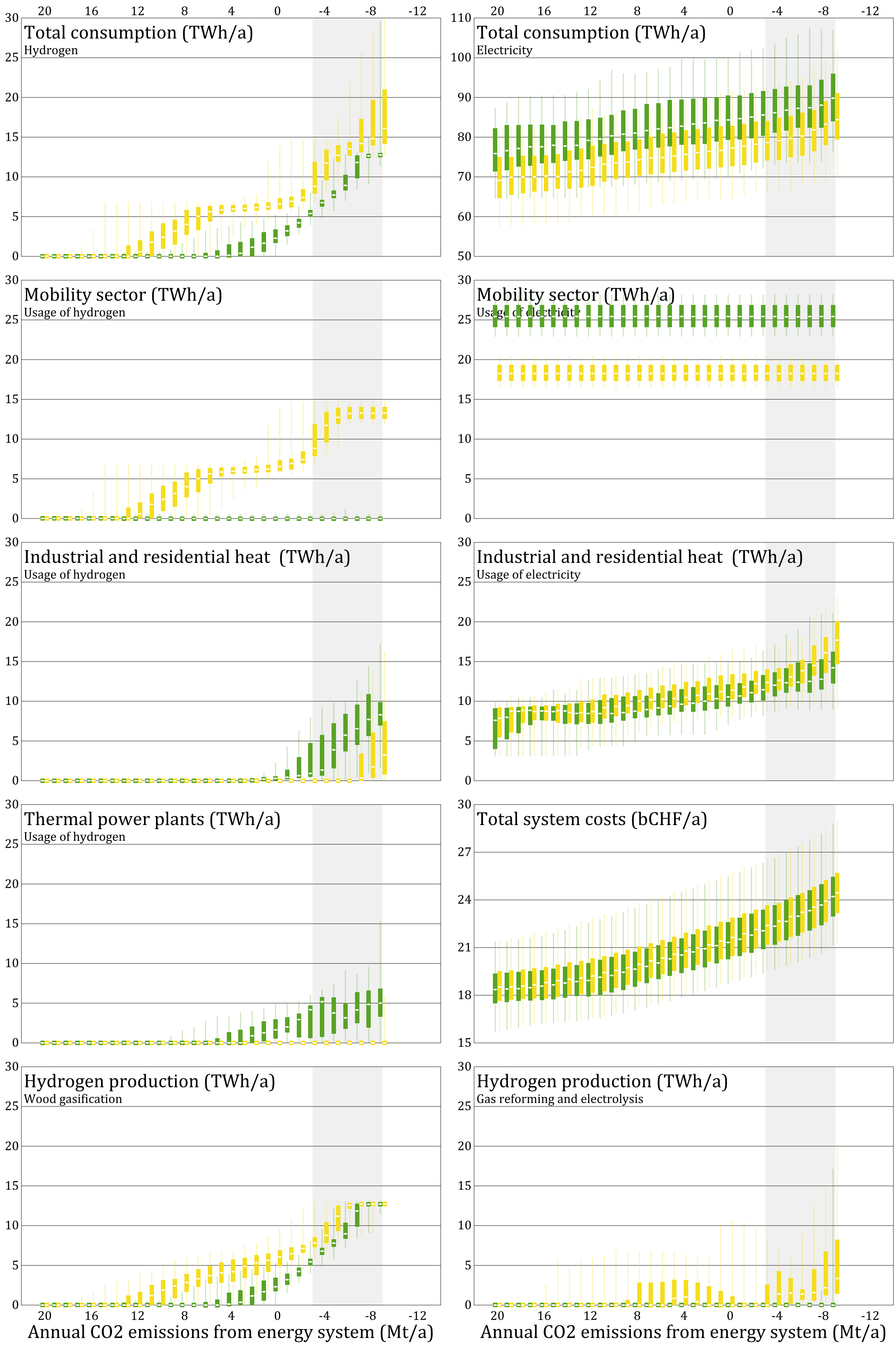


Figure 5.8: Impact of transport electrification for scenario variants Imagine and mobility all electric

electricity demand raises (top right) and hydrogen demand reduces (top left). Since hydrogen production via gasification can still deliver valuable negative emissions, the use of hydrogen shifts from mobility to industrial and residential heat, and thermal power plants. This reduced consumption is fully satisfied by wood gasification (bottom left), whereas gas reforming disappears (bottom right).

> A super battery does not reduce the importance of a hydrogen-CCS strategy nor the role of wood gasification to deliver negative emissions.

5.7 Which types of energy storage will Switzerland need?

The most common argument against an energy transition as planned by Switzerland is the unavailability of storage options. A fully integrated energy system model as SES-ETH is very well suited to give an answer to the question of how much and which types of storage are really needed in the future energy system. To analyze the role and development of energy storage, it is particularly important not to isolate the different sectors of the energy system: a need for *storage* within an isolated sector may very well be resolved by considering the *transformation* of energy forms between sectors.

In SES-ETH, we model various seasonal and short-term (hourly) storage options. Note that the typical day approach of SES-ETH does not allow us to model the intermediate timescales, i.e. several days to a few weeks. For seasonal storage, we include the options of thermal, hydrogen, methane and hydro reservoirs. The first three are actively charged, while the latter is charged by the inflow to the reservoir lakes and the model can only choose how to discharge it. For short-term storage, we model thermal, hydrogen and electrical options. We model the latter with pumped hydro storage, however, since SES-ETH has no representation of an electrical grid, electricity short-term storage could also be realized with batteries that are placed in lower voltage levels, closer to the photovoltaic generation.

Figures 5.9 and 5.10 summarize our findings on storage. The left column depicts the installed capacity in GWh, and the right column presents the annual throughput, i.e. the amount of energy that was charged and eventually discharged from the storage through the year. The top row corresponds to a residential seasonal thermal storage that could be part of a district heating network. We can see that the installed capacity and the annual throughput are in the order of 5 TWh/a. This indicates that the storage is indeed charged and discharged only once in a year. As shown in Section 3.2.2, a seasonal thermal storage may be used in conjunction with solar thermal collectors or a combined heat and power plant that has to run throughout the year. The typical case is a waste incineration plant (Figure 3.15 on page 36): the heat generated in summer cannot be fully used by the district heating network. Therefore, the additional heat has to be rejected, unless a thermal energy storage is available.

The next row in Figure 5.9 is a residential short-term thermal energy storage. Note that the scale of the left and right column now differ by a factor of 100. Comparing the installed capacity and the annual throughput shows that 100 is in fact the typical number of cycles for a diurnal storage that is most active in summer. Charging occurs through heat pumps and solar thermal collectors (Figures 3.17 on page 38 and 3.18 on page 39). The next two rows depict seasonal and short-term thermal storage for industrial process heat (see also Figures 3.9 on page 28 and 3.10 on page 29). Again, the seasonal storage option (available only for Revolution and Imagine) is charged and discharged once a year, whereas the short-term storage results in around 100-200 cycles.

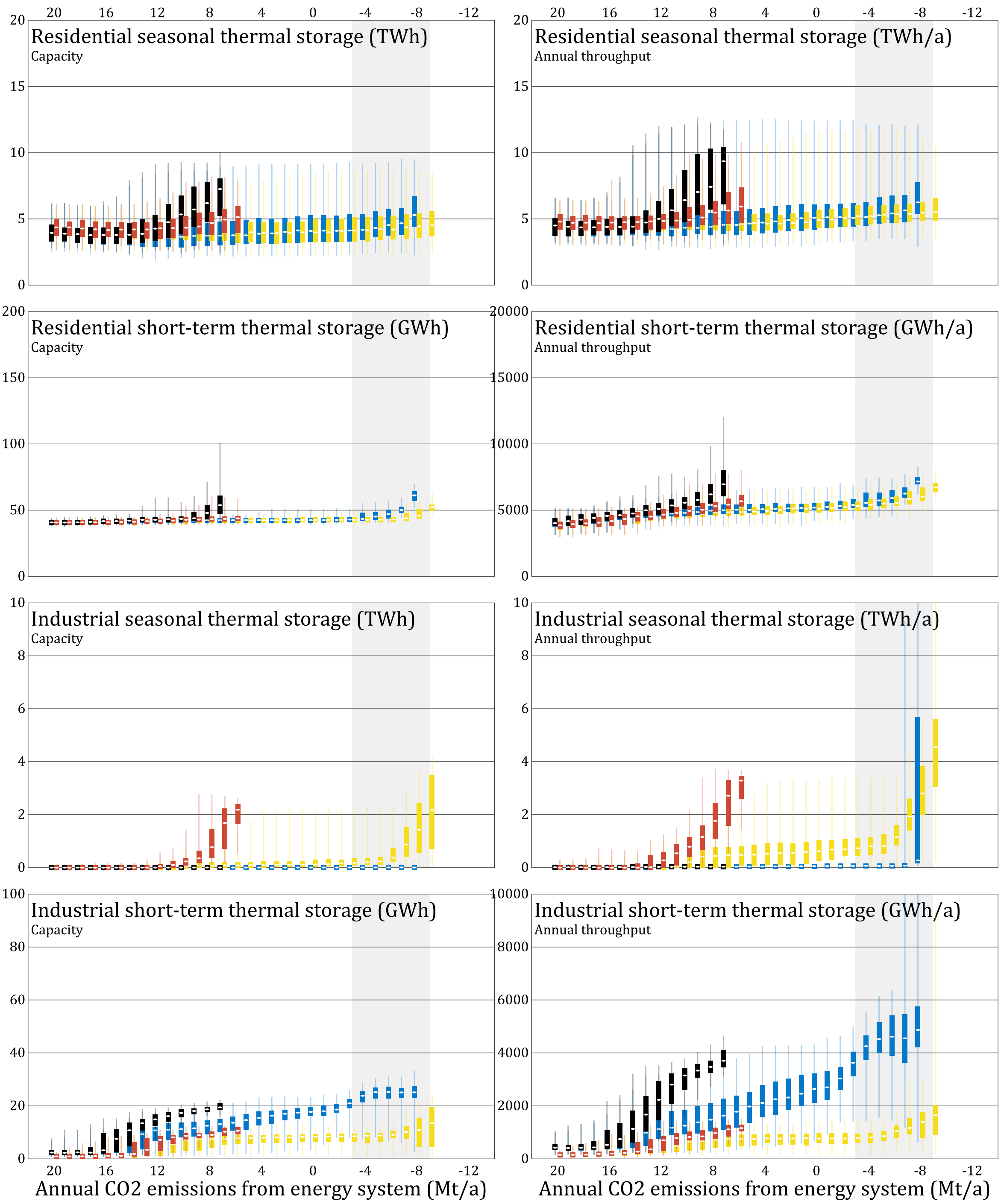


Figure 5.9: Volume and annual throughput for thermal energy storage, scenario variants Yesterday, Revolution, Come together, Imagine

Figure 5.10 shows other storage options. Hydro reservoirs are filled by the natural inflows and are charged and discharged only once a year. Today's capacity is around 6.5 TWh. Researchers in SCCER-SoE have estimated that this capacity could be increased to 8.5 TWh by increasing the dam height on selected reservoirs. This option is offered for the scenario variants Revolution and Imagine and is fully used by the model. Figure 3.30 on page 53 shows the hourly profile of the storage level of the reservoir lakes.

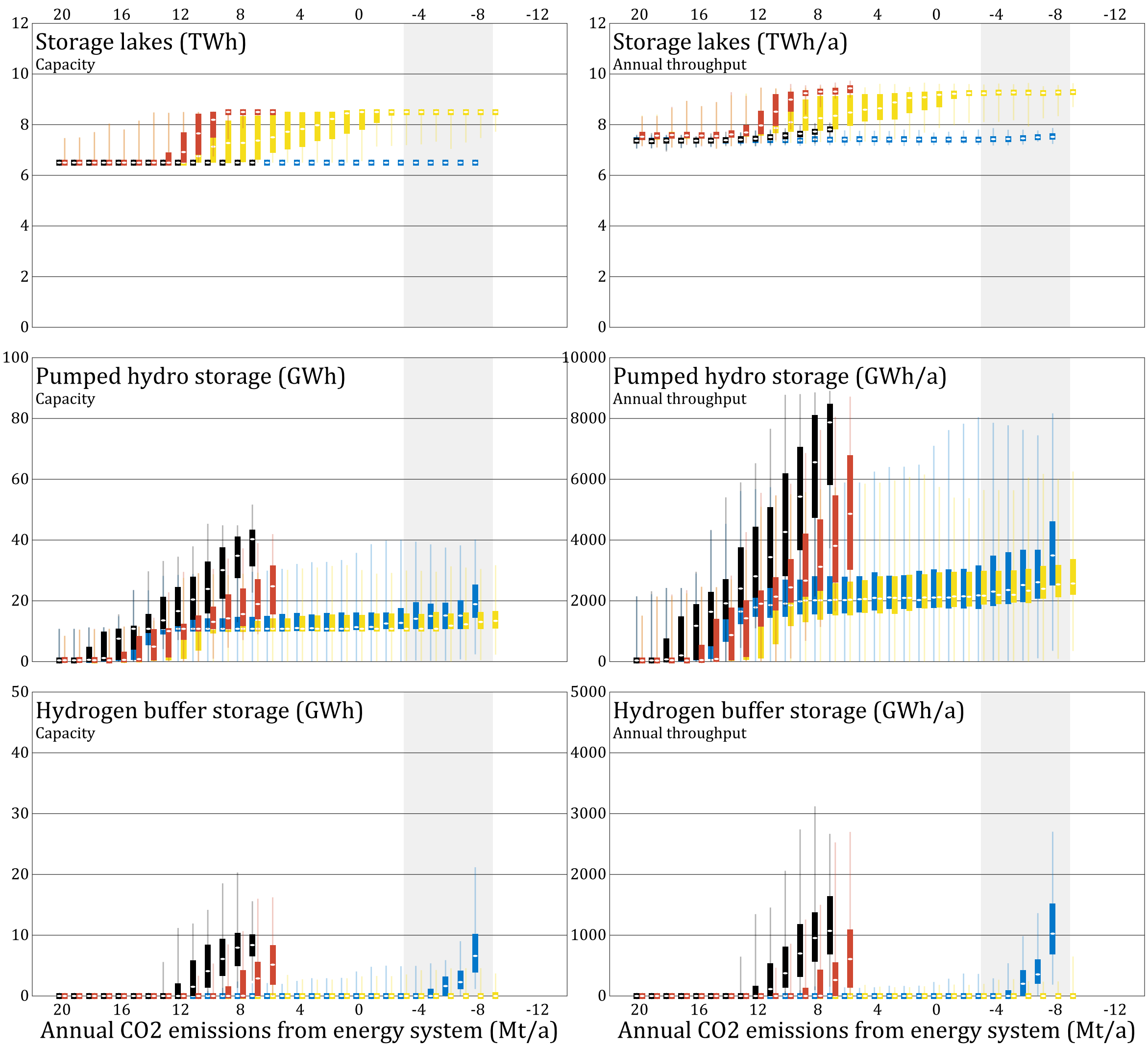


Figure 5.10: Volume and annual throughput for reservoirs, pumped hydro storage and short-term hydrogen storage, scenario variants Yesterday, Revolution, Come together, and Imagine

Pumped hydro storage acts as a short-term storage with approx. 200 cycles per year. Installed capacity and annual throughput grow with photovoltaic generation (Figure 3.28 on page 51). The summer noon peaks are absorbed and delivered during the night (Figures 3.30 on page 53 and 3.31 on page 53).

The last row in Figure 5.10 is a hydrogen buffer. Here the number of cycles is around 100. This is related to the deployment of electrolysis, as can be seen in Figure 3.24 on page 47. As we discussed in Section 3.3.1 on page 44, electrolysis (or power-to-gas) does not play a dominant role in the net-zero scenarios, therefore, also the storage requirement is low. In our results we do not find the need for a seasonal storage that moves large quantities of photovoltaic generation via hydrogen from summer to winter. For the same reason, seasonal methane storage that would result from a Sabatier conversion of hydrogen/CO_2 to methane is absent from the storage technologies.

> To summarize: Storage technologies of all kind are required. Despite the need for technological development in some fields (e.g. batteries), most options are already available today.

5.8 What is the best use for deep geothermal energy?

The Energiestrategie 2050 from 2012 (Prognos, 2012) assumed a potential for geothermal electricity of 4.4 TWh/a. One of the Swiss Competence Centers for Energy Research: Supply of Electricity (SCCER-SoE) was fully devoted to this subject. An important issue of using geothermal energy to produce electricity is that, even at a depth of 4–6 kilometers, the available temperatures are only in the range of 120–180 °C, leading to low a conversion efficiency of thermal to electrical energy of 10–15%.

In SES-ETH, we model various options for using geothermal energy: electricity generation, district heating, low temperature industrial processes and the use in CO_2 separation processes. The scenario results show that the electricity option is never chosen (Figure 3.3 on page 20). We also find that geothermal energy is always used to supply low temperature industrial processes. For the most stringent CO_2 targets, we see a switch from district heating applications to the CO_2 separation process on the flue gas of cement plants, wood gasifiers and municipal waste incinerators.

Why is electricity generation never chosen in our modelling results? It is less a question of costs, rather of effectiveness to reduce CO_2 emissions. Given the 10 TWh/a of geothermal heat that we assumed in this work, one can turn these into 1.2 TWh/a of electricity, assuming a 12% efficiency. If these 1.2 TWh of electricity were produced with a gas turbine combined cycle without CCS, the associated CO_2 emissions are 0.4 $MtCO_2$/a. If the same geothermal heat was used for district heating and would replace an 80% efficient gas boiler, the CO_2 savings are around 2.5 $MtCO_2$/a. The same argument applies to any other use as direct heat for industrial processes or CO_2 separation. In summary, using geothermal heat for electricity generation does not exploit its full potential to save CO_2 emissions.

Going for direct heat use allows the project developer to choose the depth of the well according to the required temperature level. However, an important consideration for the deployment of geothermal energy is that the depth correlates with the risk of induced seismicity. A district heating network has the lowest temperature requirement of < 100°C, which can be found at a depth of 3 km. Low temperature industrial processes require anything between 80–150 °C, i.e. 3-5 km . The highest temperature level of > 130 °C is needed for CO_2 separation, and implies a depth of 4–5 km.

Finally, an important issue with geothermal exploration is that it requires a large upfront investment, which is not ideal for industrial processes that are subject to global trends and could be moved outside Switzerland. However, district heating networks or municipal waste incinerators are likely to stay as long as the communities they serve continue to exist.

> We recommend that deep geothermal energy is first used for district heating networks, followed by the application in low temperature industrial processes.

5.9 Is wood gasification really required?

One of the surprising outcomes of our analysis is the importance of wood gasification for reaching a net-zero emission target. Gasification plays a dual role, it supplies hydrogen for mobility and industrial processes and it allows for negative emissions by stripping off atmospheric CO_2 from biomass and storing it underground.

The idea of gasification is generally received with some criticism, therefore, we analyze the effect and feasibility of using alternative technologies. Some qualitative judgement can be done before using our full energy system model. We assume that the need for hydrogen and negative emissions remains. Hydrogen can then be produced by electrolysis or by steam methane reforming with CCS. Both options, green and blue hydrogen, are in principle CO_2-neutral, but they do not allow for negative emissions. The latter can be produced by burning wood and capturing CO_2 from the flue gas. Since this requires a certain scale - both for the capture plant and for the necessary CO_2 transport infrastructure - the logical choice to replace wood gasification to hydrogen is a wood-fired thermal power plant.

Doing the experiment with our model suggests indeed a similar shift. Figure 5.11 shows the usage of methane (left) and wood (right) for various purposes. Methane use for electricity and heat generation drops whereas it grows strongly for wood. Methane is instead used for gas reforming, compensating the reduction in the hydrogen production by gasification. As a consequence of these changes, the overall system costs grow by some 800 million CHF per year.

Figure 5.12 shows the Sankey diagrams of CO_2-flows at -6 $MtCO_2/a$ for a typical case of the two scenario variants from Figure 5.11. It is clearly visible that the shift is between gasification (green) and power plants (yellow). The amount of stored CO_2 is the same, only the source is different.

Going back to our qualitative judgement, the two pathways can also be compared based on conversion efficiencies. Using wood to produce hydrogen and gas to produce electricity have efficiencies of around 60%. Using gas to produce hydrogen has an efficiency of around 60% as well, but using wood to produce electricity has a significantly lower efficiency of around 30%. Therefore, the pathway using wood gasification to hydrogen is inherently more efficient.

> We find that an alternative to wood gasification – albeit more expensive – that allows to reach the same level of negative CO_2 emissions is to burn wood in thermal power plants and to capture and store the CO_2 in the process.

5.10 What is the effect of electricity and hydrogen imports?

As explained in Section 2.1.3, we consider two variants for the treatment of electricity and hydrogen imports (Figure 2.1). In both cases, the electricity or the hydrogen are produced by gas turbine power plants and steam-methane-reforming, respectively. Both technologies consume natural gas and emit CO_2, which should be captured and stored in a net-zero emissions world. In the more conservative Option A, we consider that both the gas consumption and the CO_2 emissions are included in the Swiss gas consumption and energy-related emissions, respectively (Figure 2.1b). In Option B, we treat electricity and hydrogen imports as incoming energy streams with a certain price, and we do not account for the CO_2 emissions that are generated – and possibly stored – during production (Figure 2.1c). This variant corresponds to the way imports are treated today.

Whether or not imports of electricity and hydrogen in Option B are used by the energy system depends on the import price and its relation to the domestic marginal generation costs, i.e. the costs to generate one more unit of electricity or hydrogen in Switzerland. Figure 5.13a shows these values as yearly averages for the four core scenario variants. Focusing on Imagine, in the CO_2 target range, we can clearly see that an import price for electricity and hydrogen has to be below 150 and

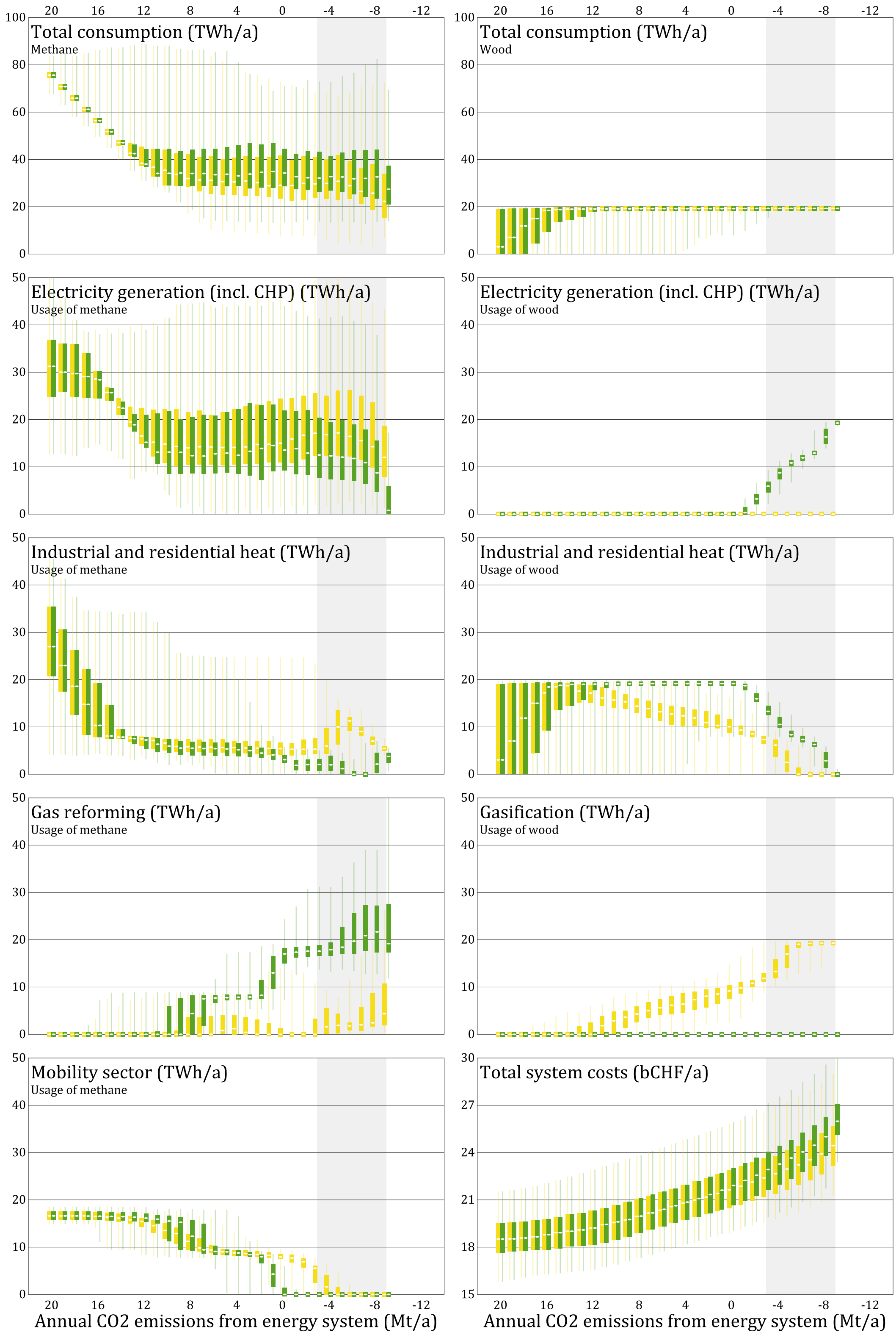


Figure 5.11: Energy streams for scenario variants Imagine and Imagine without gasification

100 CHF/MWh, respectively. The analysis done by the University of Basel using the Swissmod model suggests an average electricity import price of 100 CHF/MWh by the middle of the century (Marcucci et al., 2021b). In our analysis, we use this value and a higher and lower variant of 125 and 75

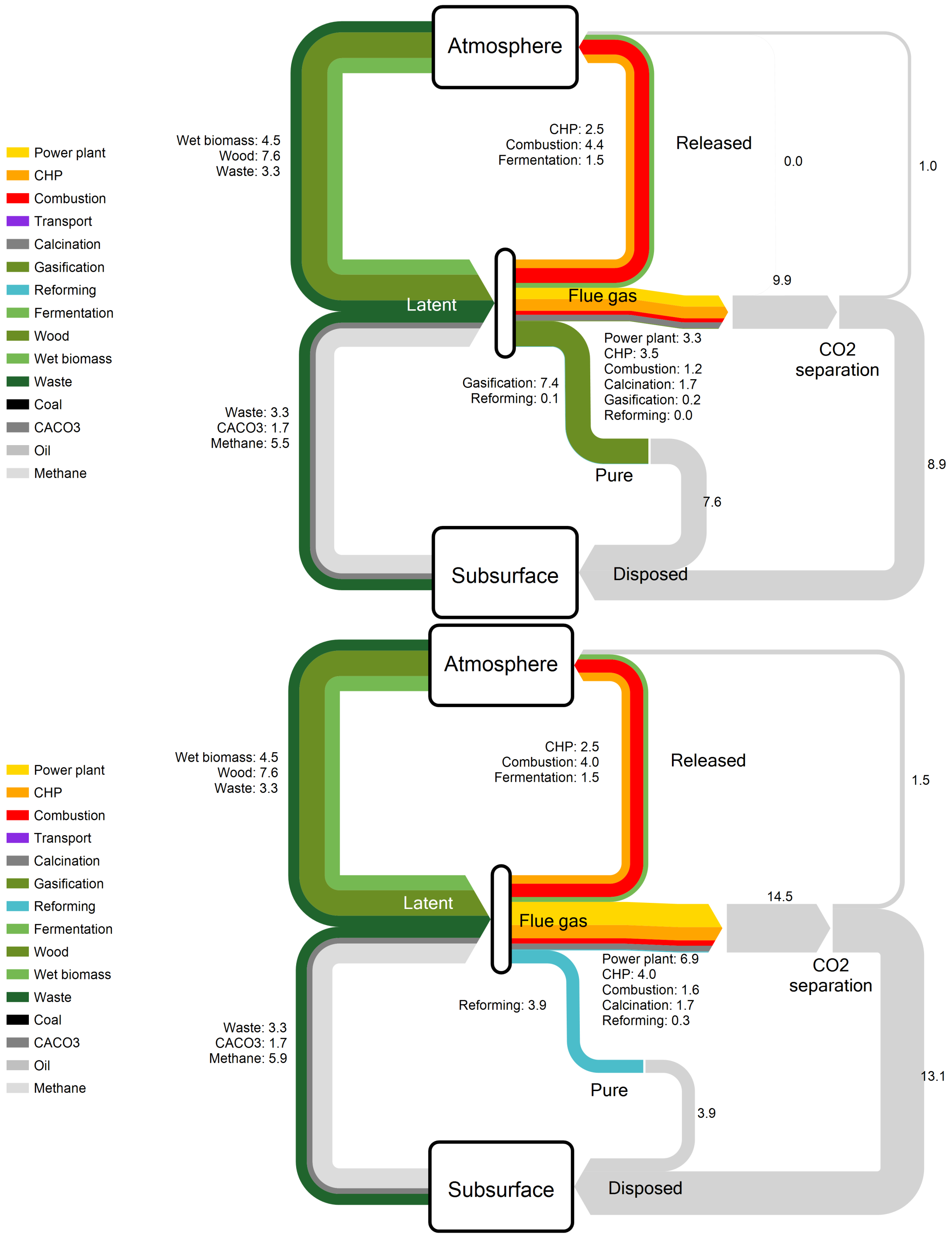
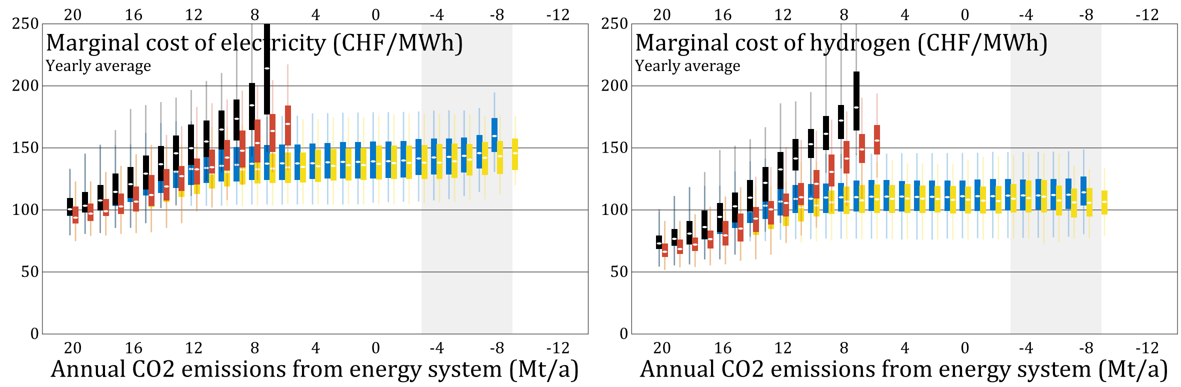


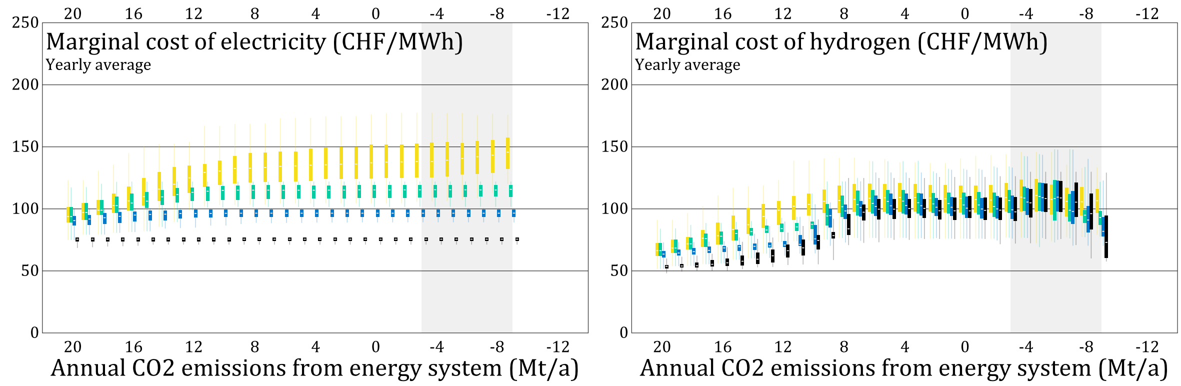
Figure 5.12: CO_2 streams for a typical case of scenario variant Imagine (top) and Imagine without gasification (bottom) at -6 Mt/a

CHF/MWh. For hydrogen imports, we use the same 75, 100 and 125 CHF/MWh. Note that this is below the latest estimates on hydrogen import prices that range from 116 to 215 CHF/MWh (Marcucci et al., 2021b).

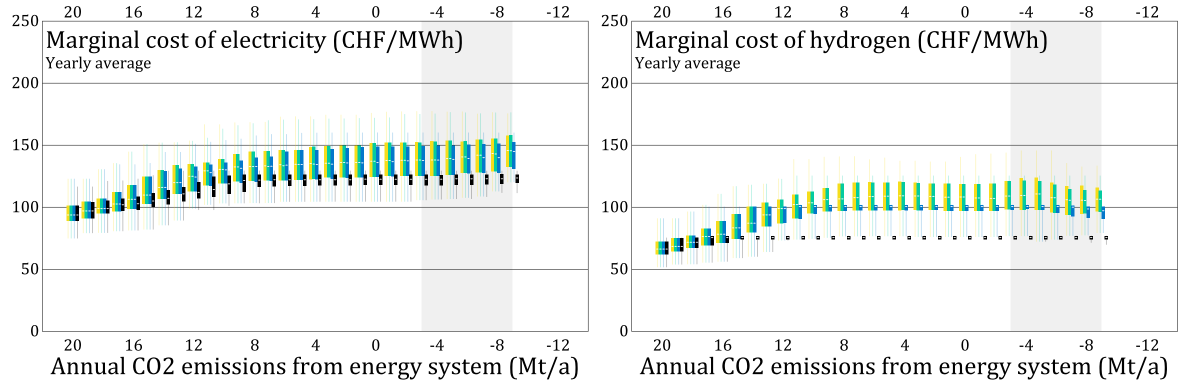
Figures 5.13b and 5.13c depict the impact of the variations on the import prices. Not surprisingly, the marginal costs follow the import prices. Moreover, we see an inter-dependency between hydrogen and electricity imports and production, i.e. when hydrogen imports reaches the lowest assumed level



(a) Scenario variants Yesterday, Revolution, Come together, Imagine



(b) Option A: Imagine, no import; Option B: *Electricity* import at 125, 100, 75 CHF/MWh



(c) Option A: Imagine, no import; Option B: *Hydrogen* import at 125, 100, 75 CHF/MWh

Figure 5.13: Marginal generation costs for electricity and hydrogen.

of 75 CHF/MWh, also the marginal electricity generation costs reduce, mainly due the switch in the fuel used in the gas turbines from methane to hydrogen.

More interesting is the effect on the supply technology mix for electricity and hydrogen. Figures 5.14 and 5.15 show the impact on electricity generation of varying electricity and import prices. For low electricity import prices, gas turbine power plants that use methane or hydrogen disappear and are replaced by electricity imports. Also generation with solar photovoltaic reduces strongly, and in the case of 75 CHF/MWh it almost disappears. Varying hydrogen import prices has a lower effect on the results on the electricity generation mix, since both thermal power generation (using hydrogen) and

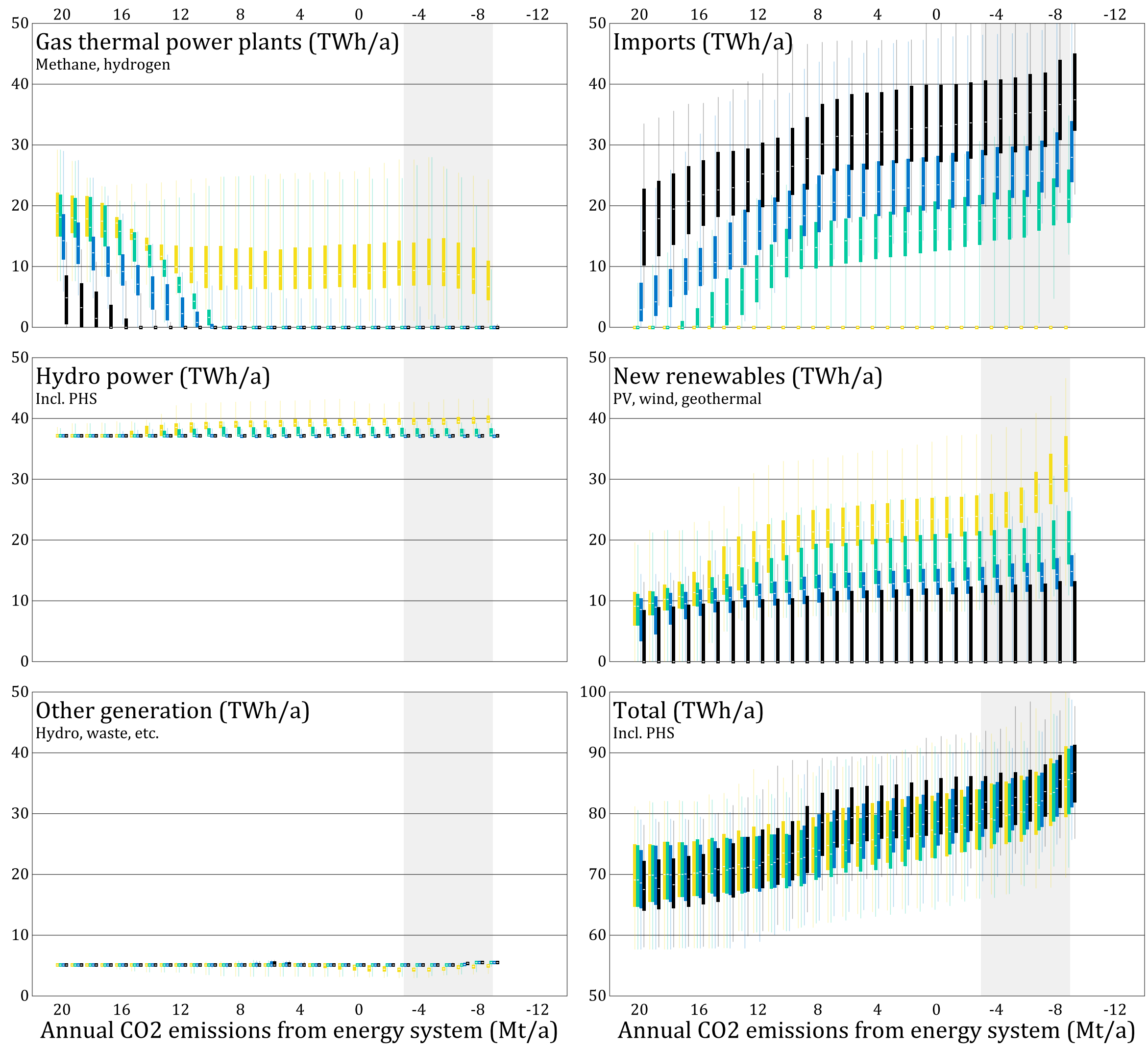


Figure 5.14: Electricity generation for different *electricity* import prices; Option A: Imagine, no import; Option B: 125 CHF/MWh, 100 CHF/MWh, 75 CHF/MWh

photovoltaics remain at a high level.

Figures 5.16 and 5.17 show the effect on hydrogen production of varying electricity and hydrogen import prices. Electricity prices have little impact on the hydrogen production mix, wood gasification remains the dominant technology, mainly due to the need for negative emissions. Low hydrogen prices imply a significantly increase in the hydrogen consumption, which is now used mainly for power generation and industrial process heat. The hydrogen used for the production in industrial process heat partially replaces the use of methane. As a consequence less negative emissions are needed and the use of hydrogen from wood gasification decreases.

Figure 5.18 shows the effect of imports on the sources and the total amount of stored CO_2. The most important takeaway is that imports have no impact on the need to capture CO_2 from waste and cement plants. Only the need to generate negative emissions through biomass gasification of solid biomass is slightly reduced.

Finally, it is interesting to evaluate the effect of imports on the total primary energy demand and the fraction of this primary energy demand that needs to be imported. Figure 5.19a summarizes the

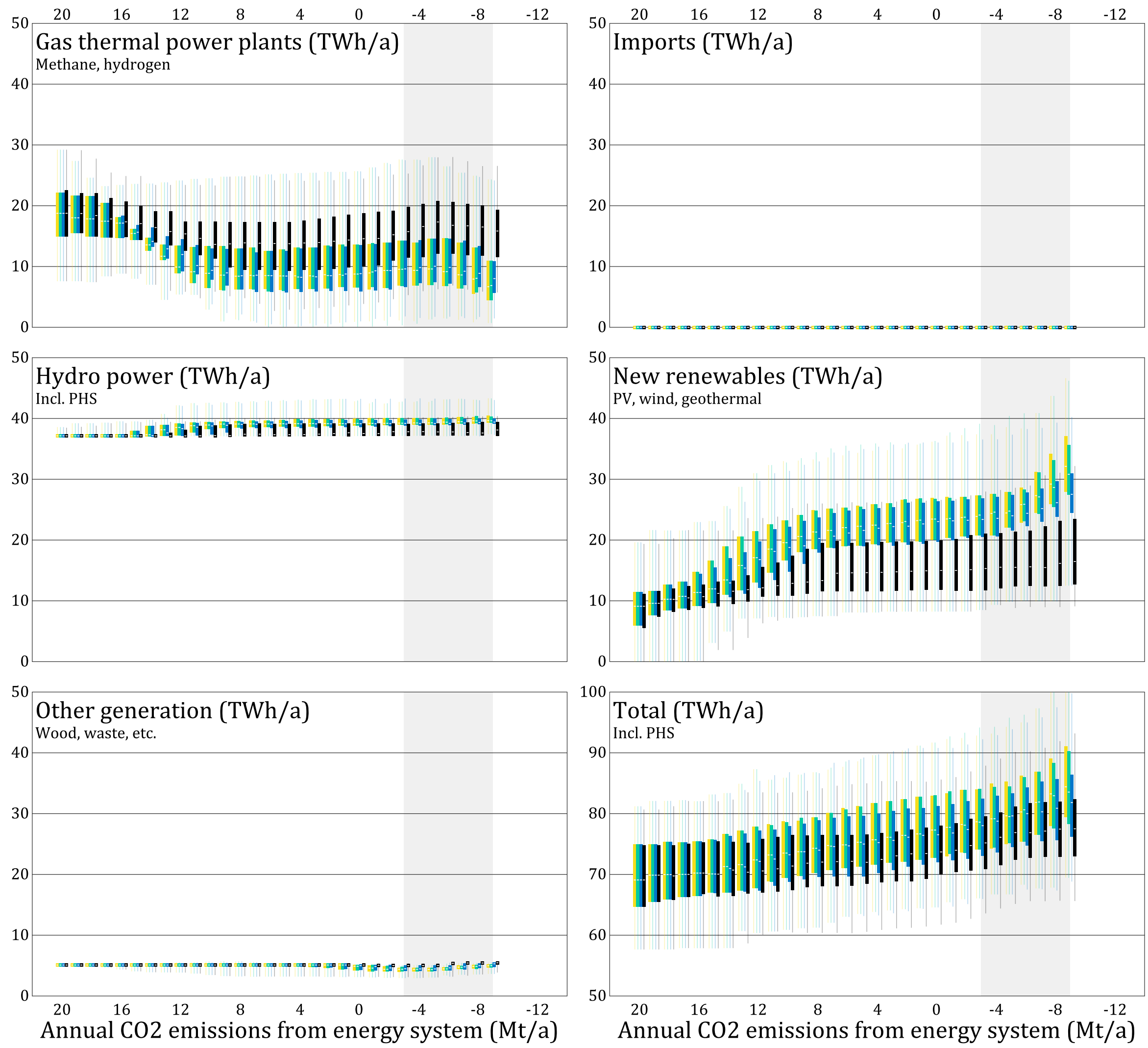


Figure 5.15: Electricity generation for different *hydrogen* import prices; Option A: Imagine, no import; Option B: 125 CHF/MWh, 100 CHF/MWh, 75 CHF/MWh

results for the four core scenarios and the variations of electricity and hydrogen import prices. It compares the imported resources (fossil gas, oil, coal and optionally electricity and hydrogen) to the total input. The import dependency, i.e. the ratio of imports to total primary energy input, reduces from approx. 40% for 20 Mt/a down to 15–30% for the lowest CO_2 targets. This ratio is highest for the lowest import prices but in any case significantly lower than the 75% that Switzerland has today. Figures 5.20 to 5.22 depict a more detailed breakdown of the various primary energy streams.

Alternative feasible designs of future energy systems emerge from this analysis. Switzerland could simply rely on electricity imports that would account for around 50% of the electricity demand in a low import price scenario of 75 CHF/MWh. Electrification of heating and mobility are needed, but investments in photovoltaics or the extension of hydropower plants would not be necessary. This is obviously a political decision outside the realm of energy system modelling. Alternative, Switzerland could import large amounts of hydrogen. In this case, the energy system is not that different from our Imagine variant. Thermal power plants would use the additional imported hydrogen to generate domestic electricity that allows the electrification of heating and mobility. Investments on solar

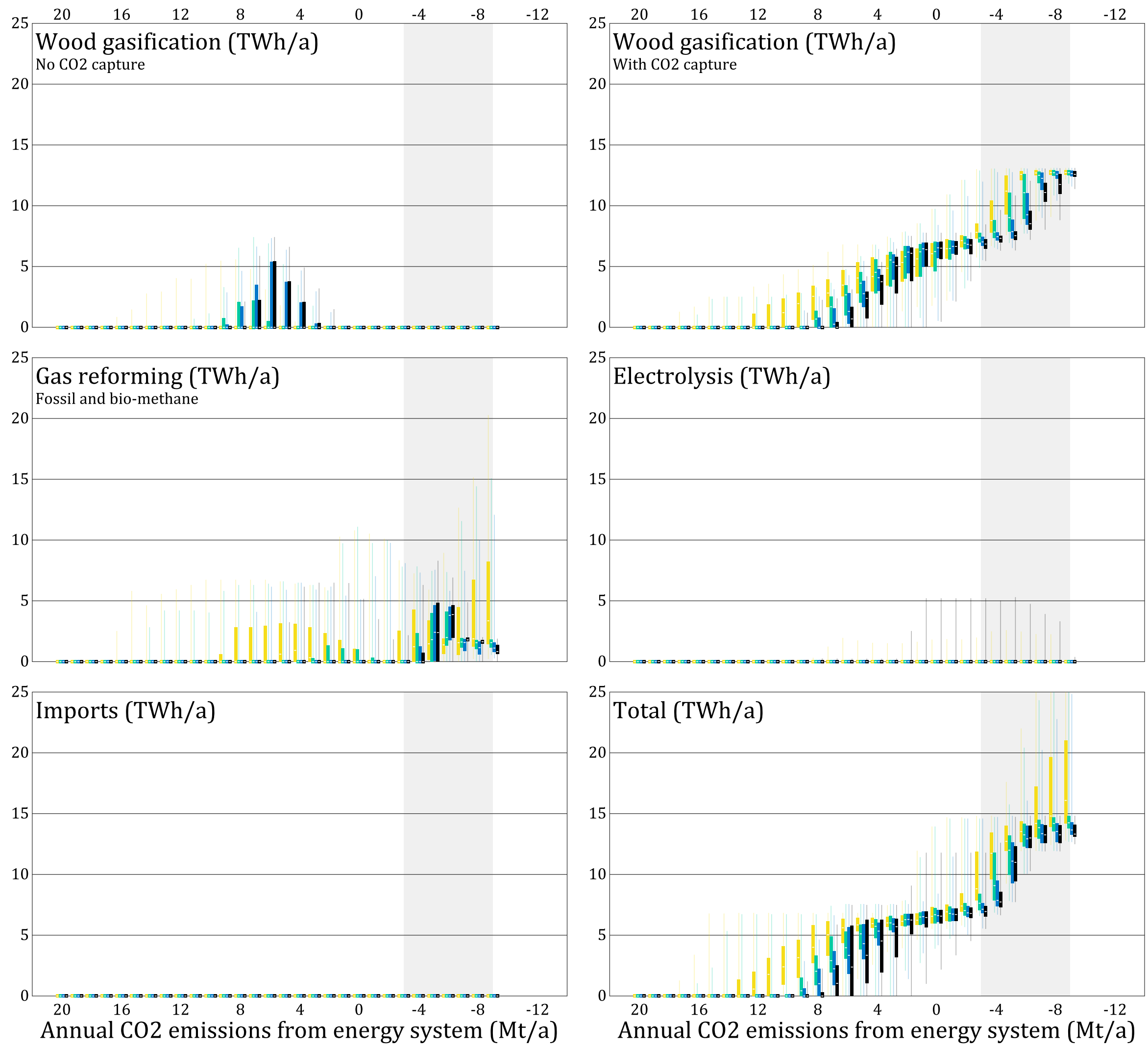


Figure 5.16: Hydrogen production for different *electricity* import prices; Option A: Imagine, no import; Option B: 125, 100, 75 CHF/MWh

PV and hydropower continue to be part of the mix, although slightly reduced. Both future energy system would need CCS and negative emissions to reach the net-zero climate target, these negative emissions could come for instance from wood gasification to hydrogen.

From an energy system perspective there is no fundamental difference whether to rely on electricity or hydrogen imports. Politically, these two options are possibly seen in a different light. Society is used to rely 100% on imported chemical energy carriers – oil and gas. Hence, relaying on hydrogen import would imply “just” a switch from oil and gas to hydrogen. However, depending heavily on electricity imports might be perceived differently. Based on our analysis, we cannot suggest a course of action, only highlight the inter-dependencies and analyze those decisions that are independent from political choices.

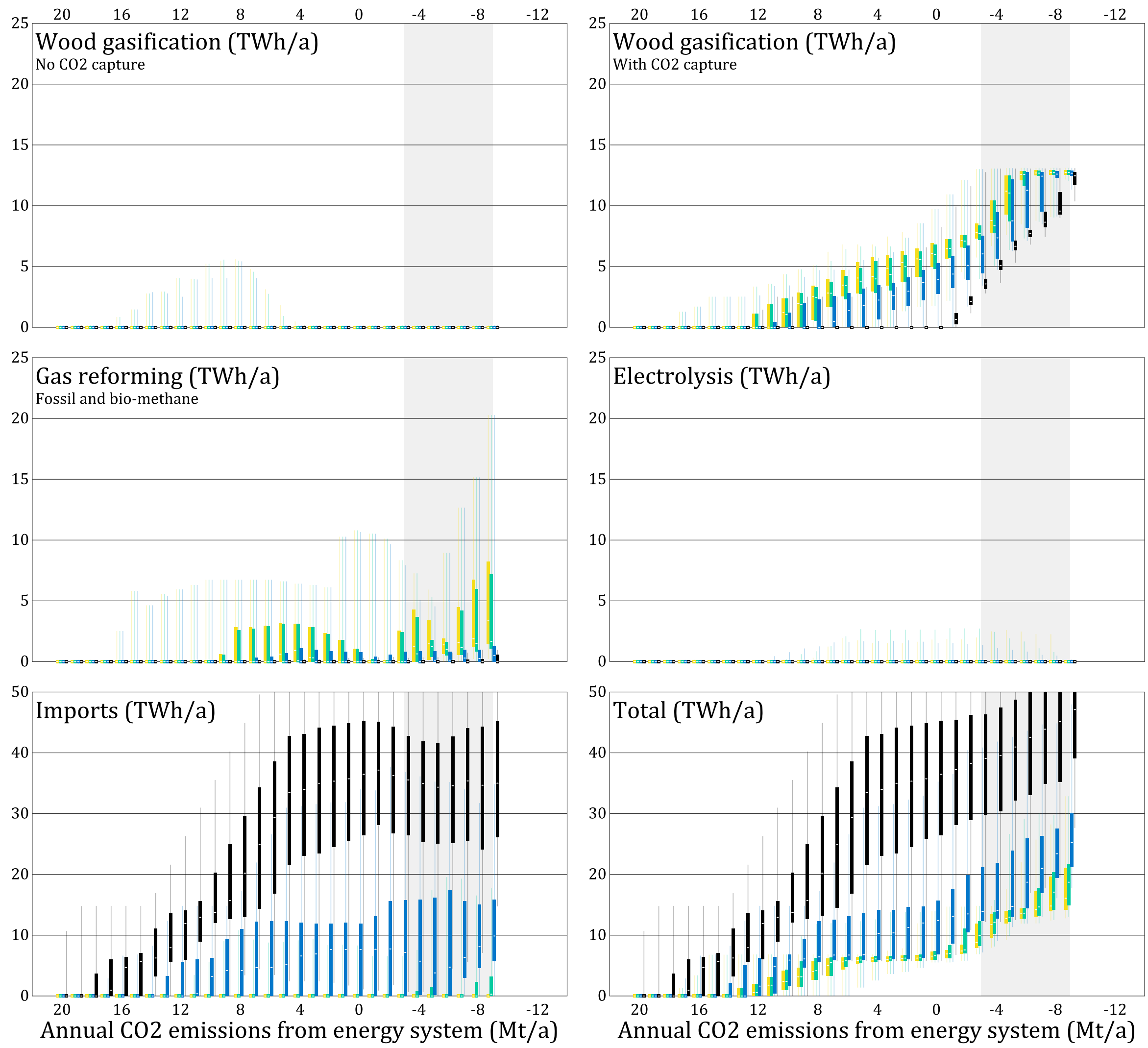
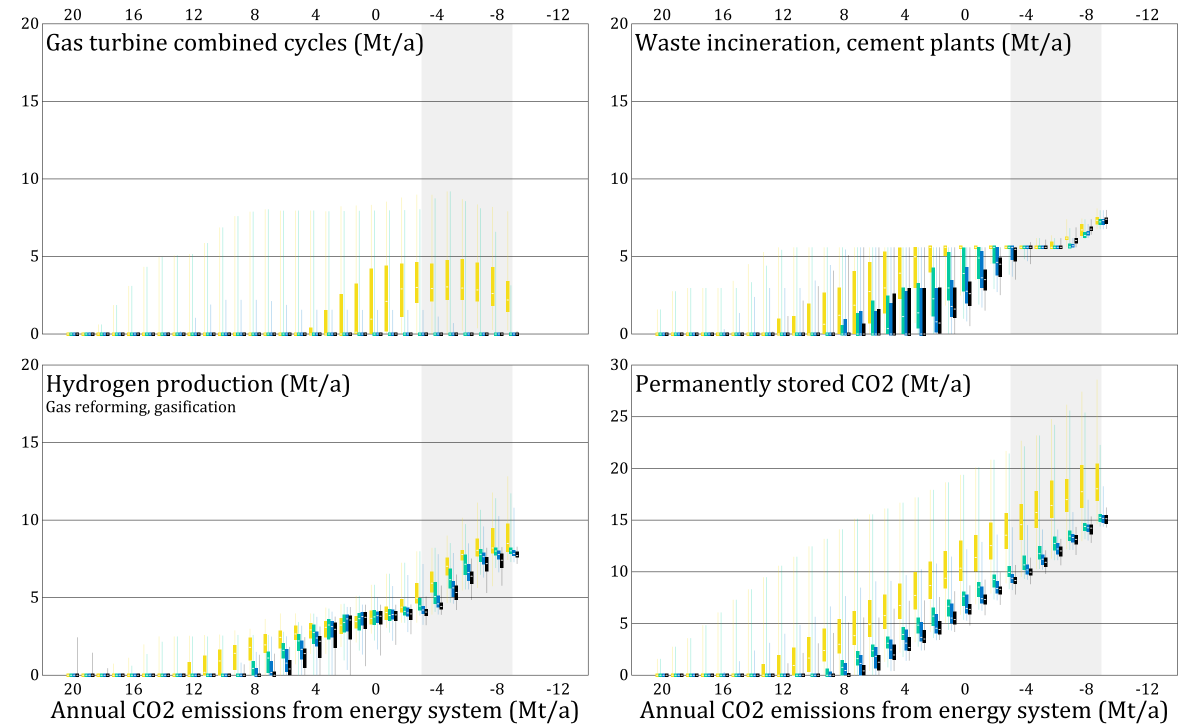
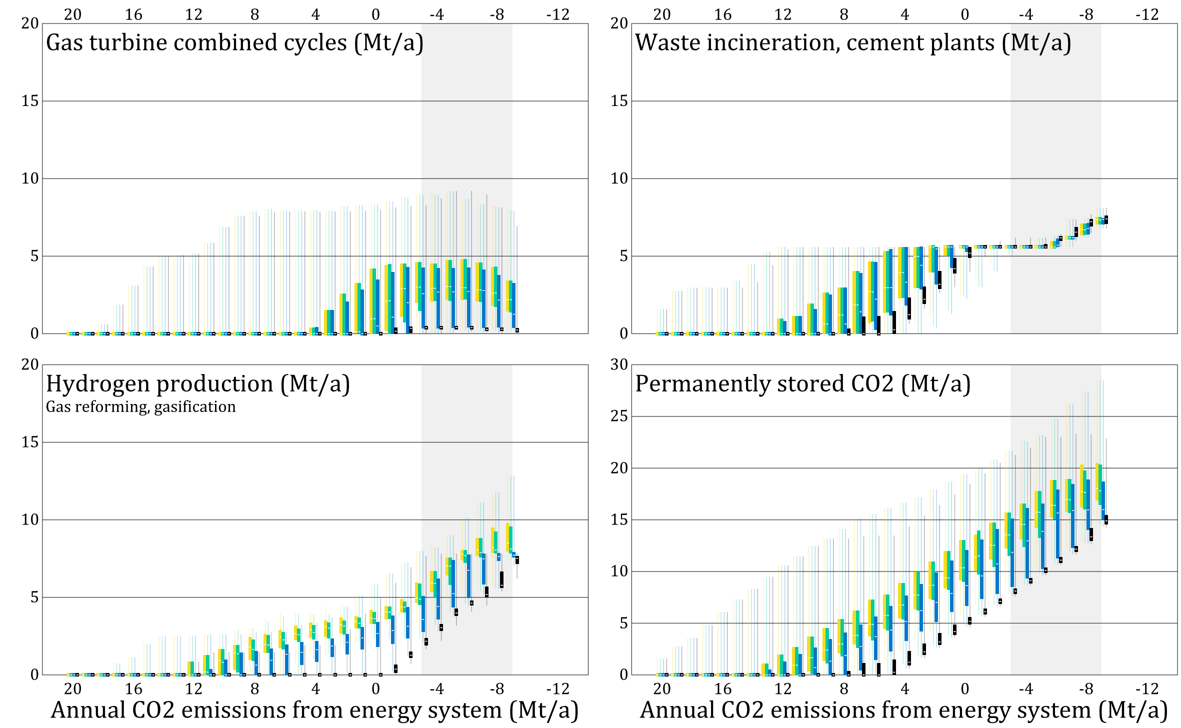


Figure 5.17: Hydrogen production for different *hydrogen* import prices; Option A: Imagine, no import; Option B: 125, 100, 75 CHF/MWh

Independently of the decision on how much to rely on imports of electricity and hydrogen, a few key insights concerning the future Swiss energy system remain: the need to use CCS to achieve the Swiss climate targets; the use of biomass to generate negative CO_2 emissions, for instance through gasification to hydrogen; electrification of heating and mobility; exploitation of additional heat sources such as solar thermal and geothermal; and a strong growth of photovoltaics electricity generation (except in an extreme electricity-import scenario).

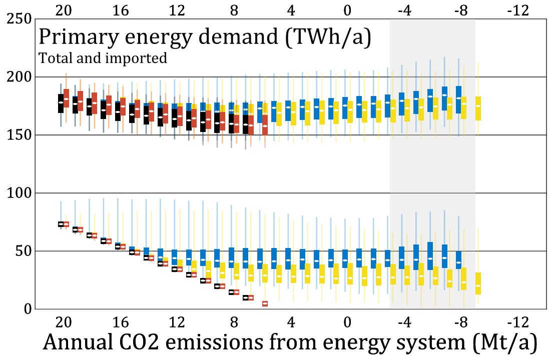


(a) Effect of varying electricity imports. Option A: Imagine, no import; Option B: *Electricity* import at 125, 100, 75 CHF/MWh

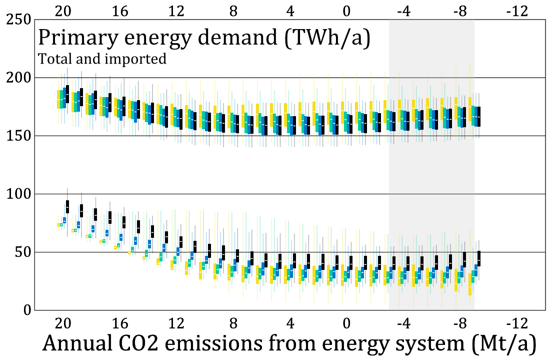


(b) Effect of varying hydrogen imports. Option A: Imagine, no import; Option B: *Hydrogen* import at 125, 100, 75 CHF/MWh

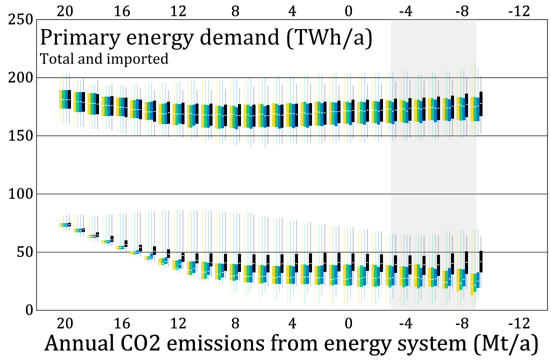
Figure 5.18: Effect of varying electricity and hydrogen imports on CO_2 streams for geological storage.



(a) Scenario variants Yesterday, Revolution, Come together, Imagine



(b) Effect of varying electricity imports. Option A: Imagine, no import; Option B: *Electricity* import at 125, 100, 75 CHF/MWh



(c) Effect of varying hydrogen imports. Option A: Imagine, no import; Option B: *Hydrogen* import at 125, 100, 75 CHF/MWh

Figure 5.19: Total and imported primary energy input.

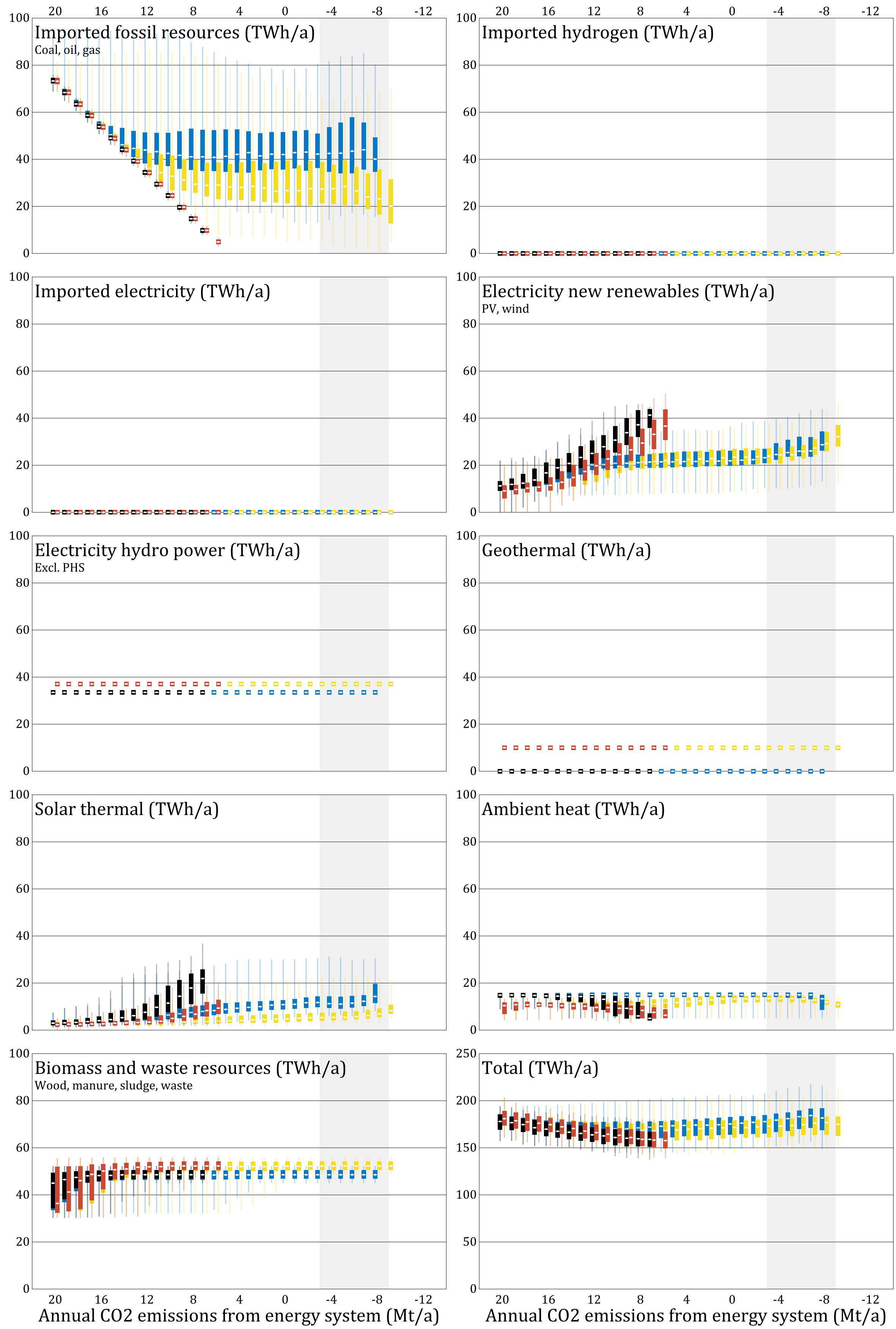


Figure 5.20: Primary energy input for scenario variants Yesterday, Revolution, Come together, Imagine

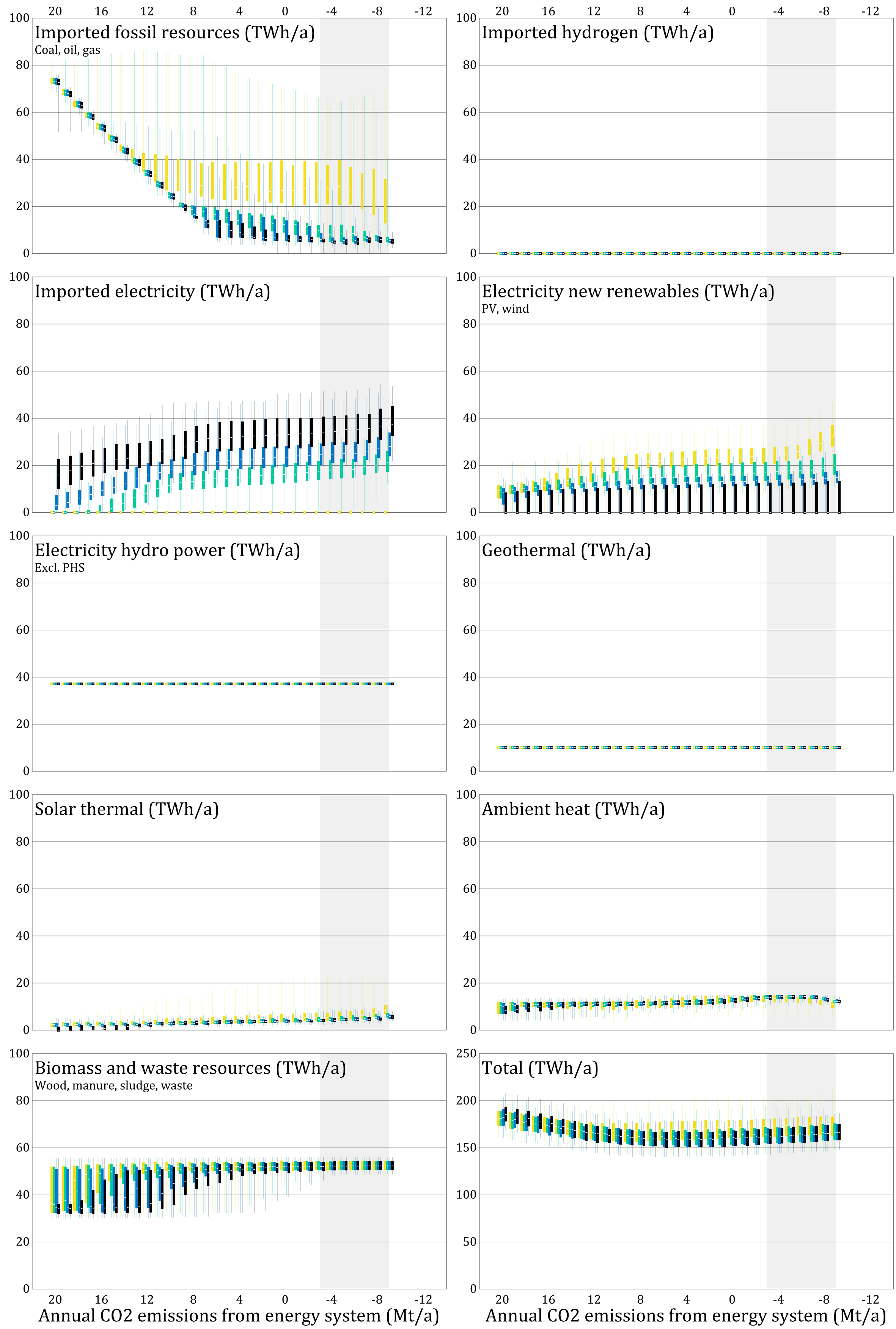


Figure 5.21: Primary energy input for different *electricity* import prices; Option A: Imagine, no import; Option B: *Electricity* import at 125, 100, 75 CHF/MWh

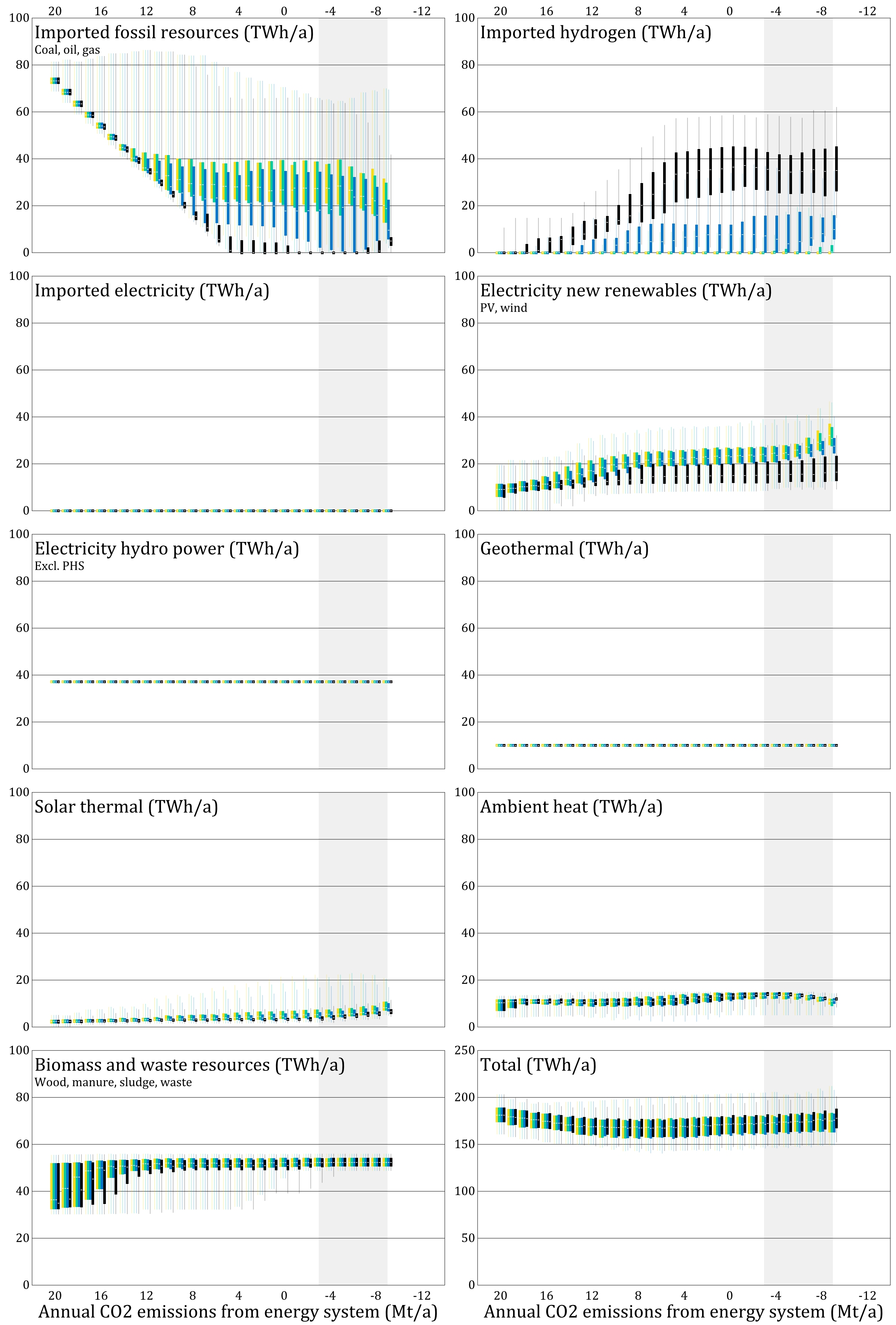


Figure 5.22: Primary energy input for different *hydrogen* import prices; Option A: Imagine, no import; Option B: *Hydrogen* import at 125, 100, 75 CHF/MWh

Bibliography

ARAMIS - Die Forschungsdatenbank, 2019. SolTherm2050 - Chancen durch Solarwärme und thermische Energiespeicher für das Energiesystem Schweiz 2050. URL: https://www.aramis.admin.ch/Grunddaten/?ProjectID=45277.

ARE, 2016. Perspektiven des Schweizerischen Personen- und Güterverkehrs bis 2040. Technical Report. Bundesamt fr̈ Raumentwicklung (ARE).

CH2018, 2018. CH2018 – Climate Scenarios for Switzerland. Technical Report. National Centre for Climate Services.

Diamond, L., 2019. Deep underground heat reservoirs, Joint NRP70 project "Hydropower and geoenergy". Technical Report. URL: https://nfp-energie.ch/en/projects/960/.

Die Bundesversammlung — Das Schweizer Parlament, 2020. Totalrevision des CO_2-Gesetzes nach 2020. URL: https://www.admin.ch/opc/de/federal-gazette/2020/7847.pdf.

Federal Council, 2019. Von welcher bedeutung könnten negative co2-emissionen für die künftigen klimapolitischen massnahmen der schweiz sein? https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/bericht-br-2.09.20-postulat-18.4211-thorens-goumaz.pdf.download.pdf/01_d_Bericht_DEzuBRAUVEK202008xx.pdf. Accessed on: 2020-11-09.

Guidati, G., Marcucci, A., Damartzis, T., Burg, V., Schildhauer, T., Giardini, D., Kröcher, O., 2021a. Biomass and waste potentials and conversion pathways for energy use in Switzerland. Technical Report. JASM and WSL. URL: https://sccer-jasm.ch/JASMpapers/JASM_biomass.pdf.

Guidati, G., Marcucci, A., Giardini, D., 2021b. Probabilistic Assessment of the Swiss Energy Stragegy - Scenario analysis with the SES-ETH model. Technical Report. ETH Zurich - JASM. URL: https://sccer-jasm.ch/JASMpapers/JASM_results_ses_eth.pdf.

IOGP – International association of oil & gas producers, 2019. The potential for CCS and CCU in Europe. Report to the thirty second meeting of the European Gas Regulatory Forum 5-6 June 2019. URL: https://ec.europa.eu/info/sites/info/files/iogp_-_report_-_ccs_ccu.pdf.

Marcucci, A., Guidati, G., Giardini, D., 2021a. Swiss Hourly Energy Scope: Documentation. Technical Report. ETH Zurich - JASM. URL: https://sccer-jasm.ch/JASMpapers/JASM_SES_ETH_documentation.pdf.

Marcucci, A., Panos, E., Guidati, G., Lordan-Perret, R., Schlecht, I., Giardini, D., 2021b. JASM framework and drivers definition. Technical Report. ETH Zurich, Paul Scherrer Institute and U. Basel - JASM. URL: https://sccer-jasm.ch/JASMpapers/JASM_drivers_framework.pdf.

Moret, S., 2017. Strategic energy planning under uncertainty. Ph.D. thesis. URL: http://infoscience.epfl.ch/record/231814, doi:10.5075/epfl-thesis-7961.

Prognos, 2012. Die Energieperspektiven für die Schweiz bis 2050. URL: https://www.prognos.com/publikationen/alle-publikationen/292/show/7f9a4382d75cc40032147306d423aaca/.

Sintef, 2020. ELEGANCY – Enabling a low-carbon economy via hydrogen and CCS. URL: https://www.sintef.no/elegancy/.

Streicher, K., Allan, J., Murray, P., Bollinger, A., Marcucci, A., 2020. Energy Efficiency from buildings retrofitting. Technical Report. U. Geneva, EMPA and ETH Zurich - JASM. URL: https://sccer-jasm.ch/JASMpapers/JASM_energyEfficiency_buildings.pdf.

Thees, O., Burg, V., Erni, M., Bowman, G., Lemm, R., 2017. Biomass for Swiss Energy Transition SCCER-BIOSWEET. Technical Report. Swiss Federal Institute for Forest, Snow and Landscape Research WSL / Swiss Competence Center for Energy Research. URL: https://www.envidat.ch/ui/#/metadata/swiss-biomass-potentials, doi:10.16904/18.

Thees, O., Erni, M., Lemm, R., Stadelmann, G., Zenner, E., 2018. Modeling the realistically sustainable potential of forest wood supplies for energetic use, in: 51th FORMEC Symposium.

Yilmaz, S., Murray, P., Bollinger, A., Guidati, G., 2020. Hourly demand profiles. Technical Report. U. Geneva and EMPA - JASM. URL: https://sccer-jasm.ch/JASMpapers/JASM_time_series.pdf.

Zuberi, M.J.S., Li, X., Wallerand, A.S., Maréchal, F., Patel, M.K., 2020. Energy Efficiency in industry. Technical Report. U. Geneva and EPFL - JASM. URL: https://sccer-jasm.ch/JASMpapers/JASM_energyEfficiency_industry.pdf.