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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech

SWEET Call 1-2021: DeCarbCH

Deliverable report

Deliverable No	D1.4.1
Deliverable name	Net-zero scenarios 2050 Focus topics: seasonal energy storage, negative emission technologies
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Delivery date	31.03.2023

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1 Executive summary

Energy system models are no design tools, they can give hints and clues what is important in a future net-zero energy system and what is not. These insights can be fed to more detailed tools and methods that allow to understand the real implications of a certain concept. We use Swiss Energyscope, an energy system model that was originally developed at EPFL and further elaborated at ETH for this purpose: to suggest directions that are worth exploring by the more technical workpackages in DeCarbCH.

This report summarizes the modelling results that were obtained by implementing the CROSS scenarios. These have two main dimensions, the level of integration with the Swiss neighbors and the ambition in reducing Swiss CO_2 emissions CO_2 domestically. We add a third dimension by defining a technology conservative and a technology innovative scenario. In addition to these base scenarios we analyze numerous variants to understand sensitivities. On top of this, we perform a Monte Carlo analysis that varies uncertain drivers such as future population count, climate or technology costs. This approach allows to determine those insights and recommendations that are stable with regards to all these variations and distinguish them from those who appear only in specific configurations.

1.1 Our current understanding of 2050

The most important general insights on a future net-zero energy system are the following:

- Electrification of mobility and heating is the crucial step towards net-zero. Electricity demand will increase from today's 60 TWh/a to 70-90 TWh/a. This demand can be covered by hydro power (33-37 TWh/a), photovoltaics (25-40 TWh/a) and a mix of other technologies, including wind power, waste, wood/gas CHP plants, and imports. Heat pumps for space heat and domestic hot water will consume some 10-12 TWh/a. Private battery electric vehicles will consume 16-18 TWh/a.
- The production profile of photovoltaics poses challenges to the energy system, that can be resolved by an array of measures. Short-term day/night variability is best tackled by electricity storage (pumped hydro and batteries), flexible regulated hydro power plants, flexible charging stations for electric vehicles, and flexible heat pumps and electric heaters with thermal storage. Long term – seasonal – variability can be addressed by increasing the capacity of hydro reservoirs, by large scale thermal energy storage that allows to run heat pumps in summer and store the heat for winter, by thermal power plants that operate in the winter months and by electricity imports.
- Besides a massive growth of photovoltaics, new energy source need to be exploited. Medium depth geothermal energy can be used to either feed into residential district heating networks or to drive low temperature industrial processes. Solar thermal energy has a similar temperature profile but requires a short to long-term thermal energy storage. In both cases a large heat pump may be needed to match the source temperature to the process requirements.
- An untapped resource that needs to be developed is agricultural biomass, i.e. manure and other residues. Results indicate that the production of bio-methane can be grown significantly. This will likely require some degree of collaboration and centralization in the rural space,

namely to collect manure and process it in larger units that allow for a connection to the gas grid. The anaerobic digestion will lead to a digestate that is today used directly as a fertilizer. Our results indicate that a further processing with hydrothermal gasification, liquefaction or carbonization can produce additional valuable chemical energy carriers.

- Besides avoiding CO_2 emissions by largely abandoning the use of fossil oil and gas, CO_2 capture and storage (CCS) will be needed, especially to avoid emissions from cement plants or to compensate non-CO_2 emissions in agriculture. The amount of CO_2 that needs to be collected, transported and stored will likely amount to 15-20 Mt_{CO2}/a. Since domestic storage of these quantities is unlikely to be possible, it is of crucial importance to connect Switzerland to a yet to be developed European CO_2 transport infrastructure. The most important negative emission technologies are indeed waste-to-energy or wood CHP plants with CCS. Any technology that produces a biogenic energy carrier, like the aforementioned anaerobic digestion and HTX technologies can contribute to negative emissions when these fuels or gases are used in installations with CCS.
- Our results indicate the benefits of being open-minded towards new technologies (Innovative vs. Conservative scenarios). Total system costs decrease and so do energy imports, especially fossil methane. Developing hydro and wind power, geothermal and the usage of agricultural biomass will require compromises but it is also a hedging strategy against volatile energy prices. In any case, overall energy imports will dramatically decrease due to the transition to electro-mobility and heat pumps.
- Variations of the base scenarios confirm the previous point: building less photovoltaics or making less wood available for the energy sector increases the needs for imports and makes us more vulnerable towards import prices.
- We also considered the possibility to import hydrogen at a price of 75 CHF/MWh as modelled within the recent VSE/Empa study. Results show that indeed large quantities of hydrogen are imported and being used for power and heat generation and for mobility. Independent of whether such low prices are to be expected, being connected to a future European hydrogen network increases our options.

A special focus in this first scenario report was put on seasonal storage. The model has several storage options implemented, i.e. hydro reservoirs, thermal storage, methane & hydrogen storage and as new option waste storage. Key findings can be summarized:

- The most important seasonal storage option is the hydro reservoirs. These lakes do not store electricity but the potential to generate electricity when it is most needed. A possible increase of the storage potential by 2 TWh was proposed in previous research. Having this available can reduce the winter electricity supply by thermal plant or imports by a similar amount of 2 TWh/a.
- Large scale thermal energy storage finds its application in combination with waste-to-energy plants, heat pumps in district heating networks and solar thermal supply of industrial process heat. Especially the combination with heat pumps has also an effect on the electricity demand. Overall, having seasonal thermal energy storage available can reduce the this in the critical winter months by 2-3 TWh/a.
- The seasonal storage of hydrogen is not an chosen option within the base scenarios. The demand for hydrogen in freight mobility is covered by steam methane reforming of imported methane (with CCS, blue H2) that operates the whole year. Only in conditions of much higher methane prices, hydrogen is produced by electrolysis (green H2), this requires also a seasonal storage to cover the constant demand over the year.

- The seasonal storage of bio-methane is an option chosen by the model, especially in the Innovative scenarios that foresee the option to strongly grow biogas production from agricultural biomass. This bio-methane is then used in the winter months for power and heat generation.
- Waste storage at waste-to-energy plants is an interesting option, especially when there is a peak capacity available at the plant. Oversizing the processing capacity of the plant only to burn more waste in winter may not be commercial.

The second focus topic was negative emission technologies. The following priorities can be derived from this analysis

- CO_2 separation and storage from waste-to-energy plants (possibly including onsite gas/wood CHP plants) should be the top priority. This option has both a large potential and a large value for the energy system. Other point sources such as cement plants or gas/wood CHP plants are technically similar.
- The proper treatment of rural biomass should receive more attention. A full industrial ecosystem can be established. This will include a centralized processing of residues such as manure in anaerobic digestion facilities, a proper biogas processing with a feed to the gas grid, a treatment of digestate in hydrothermal gasification/liquefaction or carbonization plants, a separation of CO_2 from the various processes with a connection to a CO_2 transport infrastructure (by truck, rail or pipeline). Last but not least, the proper management of nutrients as fertilizers must be considered.
- Biomass gasification is a valuable asset for the Zero scenarios but less relevant for the 6 Mt_{CO2}/a. The same is true for direct air capture. Both technologies may therefore be considered less relevant for Switzerland, however, at a global scale there is no doubt that these technologies will be essential, at least for producing sustainable aviation fuels.

1.2 Actions for DeCarbCH

The most relevant insights for heat supply can be summarized as follows:

- The decarbonization of heating is mostly achieved through the electrification. For space heat and domestic hot water in single and multi-family-houses, air- and ground-source heat pumps have the largest share. Buildings that are not suited for heat pumps are heated with wood pellets, with some solar thermal collectors to save wood in the summer months.
- District heating networks are fed by two main sources: (1) waste-to-energy plants with the optional addition of gas and wood CHP plants, and with a carbon capture facility; (2) large heat pumps that take anergy from a lake or a river. In both cases, seasonal thermal energy storage is beneficial, to improve the utilization of a valuable resource like waste, and to shift electricity consumption for heat pumps from winter to summer months.
- Low to medium temperature process heat for industry is mostly supplied by geothermal and solar thermal energy, optionally assisted by high temperature industrial heat pumps. Some heat may also come from CHP plants. In case of solar thermal energy, the use of a seasonal thermal energy storage allows to operate the installation the whole year.
- Chemical energy carriers such as wood, waste, (bio-)methane or hydrogen are reserved for high temperature process heat, especially for the most demanding application in cement plants. Electrical resistance heaters play an important role, they absorb part of the photovoltaic peaks in the summer months at noon. With the help of a short-term thermal energy storage, this system can operate day and night.

These findings are important for DeCarbCH as they suggest technical combinations that can be further explored by the more technical WPs 3, 4 and 5. A simple energy system model like SES-ETH will never be able to study all implications of a real technical system (temperatures, hydraulics, transients, etc). We suggest to especially focus on (1) district heating networks with large heat pumps and a seasonal thermal energy storage, (2) solar thermal collector fields with seasonal thermal energy storage for medium temperature process heat, (3) the development of geothermal energy for medium temperature process heat, and (4) the use of electric resistance heaters with a thermal energy storage for high temperature process heat. (2) and (3) should be optionally coupled with an industrial heat pump to match the source and sink temperature.

1.3 Outlook to next year

The continuation of the scenario work will be embedded in SWEET-Cosi and will develop along with this new project. Question will be addressed as they arise in the course of the year. One plan for next year's update report is to implement and test various thermal storage options that may enable seasonal storage at single or multi-family house level. These will be phase change material storage, sodium-hydroxide thermo-chemical storage, and ice storage.

2 Basic model setup

In the present report we use the Swiss Energyscope model [2], which was developed at ETH Zurich based on the original model by Stefano Moret from EPFL [1]. SES-ETH is a linear optimization model of the energy system. It determines the investment and operation strategies that minimize the total annual cost of the energy system, given the end-use energy demand, the efficiency and costs of the conversion technologies, and the availability and costs of the energy resources.

SES-ETH represents the main energy demands: electricity, heat and mobility (Figure 1). It is a snapshot model, i.e., it models the energy system in a target year but it does not make any statements on the trajectory to reach this future state. The original SES included monthly periods that could capture the seasonal aspects of generation, demand, and storage. We have further developed the model to include an hourly resolution that allows us to represent the intra-day variations of the energy demand and resource availability [2]. Note that all inputs and results in this report refer to the target year 2050.

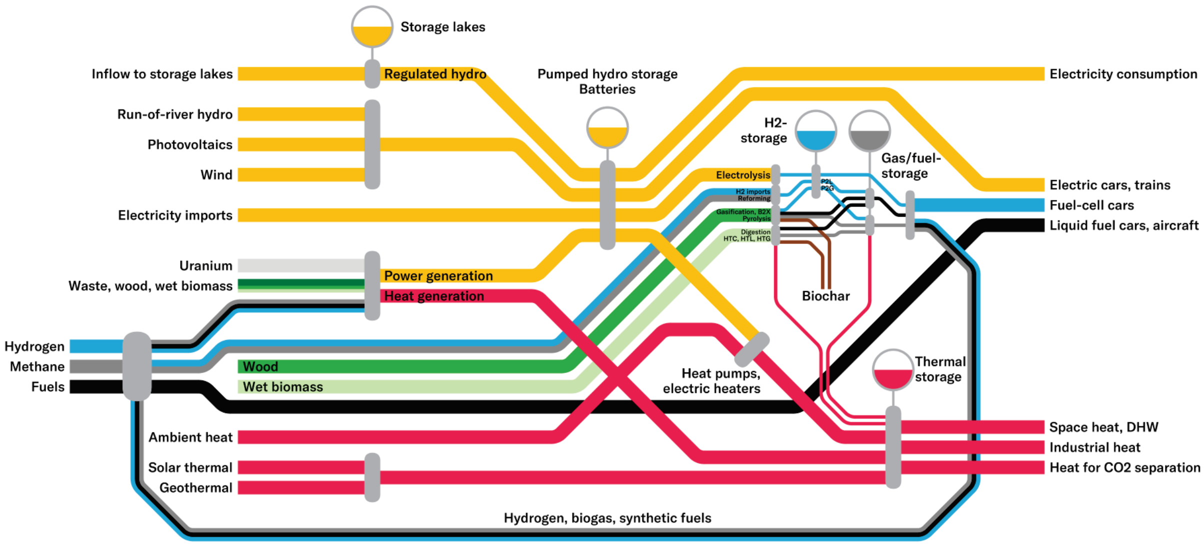

Figure 1: Schematic representation of the energy system as modelled in SES-ETH.

2.1 Layers, technologies, storage and demands

The basic setup of the model is simple (see Figure 2). A matrix is formed by columns that represent quantities such as energy (electricity, thermal energy, methane), materials (CO_2, cement) or other items such as person- or ton-kilometers. These columns are termed layers and indexed with the letter l. The rows of the matrix represent technologies that feed into layers or connect layers between each other. As an example, the gas turbine technology ① subtracts 1 MWh of methane from the methane layer and adds 0.6 MWh of electricity to the electricity layer, corresponding to an electrical efficiency of 60%. At the same time, 0.2 t_{CO2} are moved from the chemically bound layer to the flue gas layer. This ratio is determined by the CO_2 intensity of methane that is 0.2 t_{CO2}/MWh. A heat pump ② uses 3 MWh from the ambient heat layer and 1 MWh from the electricity layer to deliver 4 MWh of useful heat to a layer representing space heat for a building. This corresponds to a coefficient of performance of 4. A CO_2 separation plant ③ extracts 1 t_{CO2} from a flue gas layer and delivers 0.9 and 0.1 t_{CO2} to a pure CO_2 layer and the atmosphere, respectively, consuming 0.1 MWh of electricity. Methane import ④ delivers one MWh of energy to the methane layer and 0.2 t_{CO2} to the chemically bound CO_2 layer.

The supply of wood ⑤ delivers 1 MWh of wood to the wood layer and 0.36 t_{CO2} to the chemically bound CO_2 layer but extracts at the same time 0.36 t_{CO2} from the atmosphere. Some technologies such as photovoltaics ⑥ have only a single entry, they deliver electricity into the according electricity layer.

As shown in Figure 2, three additional matrices are used that share the same layers as columns. The storage charge and discharge matrices connect storage technologies to layers, where numbers below 1 indicate storage losses. Finally, the demand matrix connects demands to layers. Here it is important to note that not all layers have associated demands. As an example, wood is consumed to generate thermal energy for heating. The demand is heating, not the wood itself. At the same time there is no demand for hydrogen. Hydrogen may be used to generate process heat or traction in a fuel cell vehicle, then the demand is heat or ton-kilometers. Below is the fundamental set of linear equations for the decision variables $P_i(t)$, $S_j^{in}(t)$ and $S_j^{out}(t)$ that need to be satisfied in each time step for each layer.

$$\underbrace{\sum_{i=1}^{N_T} P_i(t) p_{i,l}}_{\text{Technologies}} + \underbrace{\sum_{j=1}^{N_S} S_j^{in}(t)}_{\text{Storage charge}} + \underbrace{\sum_{j=1}^{N_S} S_j^{out}(t)}_{\text{Storage discharge}} = \underbrace{\sum_{k=1}^{N_k} D_k d_{k,l}}_{\text{Demand}} \qquad l = 1..N_l$$

The storage level S_j^{level} is balanced considering the charging power $S_j^{in}(t)$, discharging power $S_j^{out}(t)$ and the efficiency matrices $\eta_{j,l}^{in}$ and $\eta_{j,l}^{out}$.

$$S_j^{level}(t+1) = S_j^{level}(t) + S_j^{in}(t)\eta_{j,l}^{in} - \frac{S_j^{out}(t)}{\eta_{j,l}^{out}} \qquad j = 1..N_S$$

Further conditions are that the decision variables have to be less than a maximum installed capacity

$$P_i(t) < \hat{P}_i \quad i = 1..N_i$$

$$S_j^{in}(t) < \hat{S}_j, \quad S_j^{out}(t) < \hat{S}_j \quad j = 1..N_S$$

And that the storage level is between 0 and the installed capacity

$$0 \leq S_j^{level}(t) \leq \hat{S}_j^{level} \quad j = 1..N_S$$

The optimization objective is to minimize total system costs which are the sum of annualized investment costs, resource costs, and fixed and variable operation & maintenance costs. The main side condition is that the total CO_2 emissions have to meet a given target. The full model is described in the original thesis by Moret [1].

Layers

			CO2 (ton)					Energy carriers (MWh)						Space heat / DHW (MWh)					Mobility (pkm)		
			Chemically bound	Flue gas	Pure	Atmosphere	Stored	Ambient heat	Methane	Gasoline	Wood	Electricity	Hydrogen	Gas boiler	Pellet boiler	Heatpump	DHN, wood CHP	DHN, geothermal	ICE	BEV	FCEV
Technologies		Ambient HEX						1													
	④	Methane import	0.2						1												
		Gasoline import	0.26							1											
	⑤	Wood supply	0.36			-0.36					1										
		Electricity import										1									
		Hydrogen import											1								
		Hydro power										1									
	⑥	Photovoltaics										1									
		Wind										1									
	①	Gas turbine	-0.2	0.2					-1			0.6									
		Gas boiler	-0.2			0.2			-1					0.9							
		Pellet boiler									-1				0.8						
		Wood CHP									-1	0.2					0.6				
		Geothermal																1			
	②	Heat pump						-3				-1				4					
		Electrolysis										-1	0.6								
		ICV	-0.26			0.26				-1									0.3		
		BEV										-1								0.1	
		FCEV											-1								0.2
	③	CO2 separation		-1	0.9	0.1						-0.1									
		Direct air capture			1	-1						-0.4									
		CO2 storage			-1		1														
Storage charge		Batteries										-1									
		Thermal storage														-1					
		Hydrogen storage											-1								
Storage discharge		Batteries										0.8									
		Thermal storage														0.9					
		Hydrogen storage											0.9								
Demand		Lights, motors, etc										-1									
		Space heat, DHW														∑ = -1					
		Mobility																		∑ = -1	

Technologies: I/O Matrix $p_{i,l}$

Storage charge / Storage discharge: Storage matrices $\eta_{j,l}$

Demand: Demand matrix $d_{k,l}$

Figure 2: Basic model setup.

2.2 Archetypes

The model has no spatial resolution, there is only one wind turbine that represents all wind turbines, one photovoltaic installation, etc. For electricity this simplification is justifiable by making the usual assumption of a copper plate, i.e. an ideal electrical network. Also for methane, hydrogen, wood and other energy carriers a transport over long distances is feasible. However, this assumption is invalid for other energy forms such as heat or the motion force in transport. Therefore, the respective demand streams are broken down into archetypes that are not connected.

An example is a gas boiler and a heat pump. Assume that one dwelling is equipped with a gas boiler, another with a heat pump. It may be beneficial to operate the heat pump mostly in summer and the gas boiler in winter. However, the two dwellings cannot exchange heat, therefore the complete demand has to be sliced in two portions that have to be satisfied independently by the two technologies. Another example is a Diesel car and a battery electric vehicle. The model could choose to run the BEV only in summer and the Diesel in winter, however, a car owner has either one or the other car, again the demands are split and have to be satisfied separately. Within individual archetypes, a mixture of technologies is indeed possible, e.g. a pellet boiler with a solar thermal collector.

The split of demand into archetypes is realized in the model by variable entries in the demand matrix $d_{k,l}$ (see Figure 2). These variables are free for the optimization with the additional linear constraint that they have to sum up to 1. Table 1 and 2 lists all archetypes currently defined. More can be added easily.

Table 1: Archetypes for space heat and DHW.

Single and multi-family houses		**District heating networks**	
DEC1	– Ground-source heat pump – Electric heater – Solar thermal – Short-term TES	DHN1/MTH4	– Waste-to-energy plant – Wood CHP plant – Gas CHP plant – Auxiliary gas boiler – Short-term TES – Seasonal TES (optional)
DEC2	– Air-source heat pump – Electric heater – Solar thermal – Short-term TES	DHN2	– Mid-sized gas CHP plant – Auxiliary gas boiler – Solar thermal – Short-term TES – Seasonal TES (optional)
DEC3	– Water-source heat pump – Electric heater – Short-term TES – Long-term ice storage	DHN3	– Wood CHP plant – Solar thermal – Short-term TES – Seasonal TES (optional)
DEC4	– Gas boiler – Solar thermal – Short-term TES	DHN4	– Small rural biogas plant – Solar thermal – Short-term TES – Seasonal TES (optional)
DEC5	– Oil boiler – Solar thermal – Short-term TES	DHN5	– Water-source heat pump – Electric heater – Solar thermal – Short-term TES – Seasonal TES (optional)
DEC6	– Wood boiler – Solar thermal – Short-term TES	DHN6	– Deep geothermal source – Solar thermal – Short-term TES – Seasonal TES (optional)
		DHN7	– Small gas CHP plant – Solar thermal – Short-term TES – Seasonal TES (optional)
		DHN8	– Pyrolysis plant – Solar thermal – Short-term TES – Seasonal TES (optional)

Table 2: Archetypes for industrial process heat.

Medium temperature (<150 °C)		**High temperature (>150 °C)**	
MTH1	– Methane/hydrogen CHP – Electric heater – Solar thermal – Short-term TES – Seasonal TES (optional)	HTH1	– Gas/oil burner – Electric heater – Short-term TES
MTH2	– Wood/waste CHP – Electric heater – Solar thermal – Short-term TES – Seasonal TES (optional)	HTH2	– Wood/waste burner – Short-term TES
MTH3	– Deep geothermal – Electric heater – Solar thermal – Short-term TES – Seasonal TES (optional)	HTH3	– Cement plant – Wood/waste burner
MTH4/DHN1	– Waste-to-energy plant – Wood CHP plant – Gas CHP plant – Auxiliary gas boiler – Short-term TES – Seasonal TES (optional)		

2.3 Typical days

In order to reduce the computational effort we use a typical day approach. Since the seasonality of energy production and demand play a crucial role in a future net-zero energy system, this aspect has to be properly reflected in the choice of typical days. The procedure consists of the following steps:

- Starting point is a full hourly time series for all quantities of interest. This series is cropped to 8640 hours or 360 days to allow for a simpler splitting into typical days.
- 360 has a large number of dividends, we are interested in those that are multiples of 12, i.e. 12, 24, 36, 60, 72, 120 and 180. This allows to clearly assign typical days to the 12 months of the year. For reasons of computational effort we choose only 12, 24, 36 and 60 typical days.
- Each choice of typical days is related to a cluster of days to choose from. For 12 typical days, the first typical day is chosen from days 1-30 of the year, the second from days 31-60, etc. For 36 typical days, the first is chosen from days 1-10, the second from 11-20, etc.
- Within each cluster the average of the quantity of interest is determined. Then the day is chosen which is closest to this average. In addition the selected day is scaled to match the average.
- Besides choosing typical days, a second measure is implemented to reduce computational effort, namely intra-day clustering. Here we choose four variants, the full 24 x 1h, then 8 x 3h clusters, 3 x 8h and finally a single 24 h cluster.

Figure 3 shows the resulting timeseries and duration curves for photovoltaic generation and 12 typical days. The monthly average of generation is properly represented by all intraday clusters, however, intra-day variability of PV generation is obviously missing for a single 24 h cluster. Nevertheless, even a simple representation by 3 x 8h clusters keeps the basic feature that PV generates only during the day. The duration curve reflects this: a 24 hour cluster smears the curve, whereas 3x8h, 8x3h and 24x1h clusters match fairly well the original duration curve of the full data set (red). Figure 4 shows the representation of photovoltaic generation for 36 typical days.

Figure 5 and Figure 6 display another important quantity that exhibits a strong seasonality, namely the demand for space heat in a typical single family house. Here it can be seen that a higher number of typical days is better suited to capture the peak demand, which in an optimization model like the present is important for the dimensioning of assets such as heat pumps or gas boilers.

In order to understand the impact of typical days / intraday clustering on the results a number of variations were analyzed. We use the latest CROSS scenarios as benchmark (see Section 3). Figure 7 shows a number of interesting quantities and their dependence on the 3 x 2 x 2 scenario variants and the number of typical days (12, 24, 36 and 60, all for 8 x 3h intraday clusters). Generally, the influence of typical days is limited. There is a slight increase especially for winter power supply and total power generation. The parallel increase in the share of heat pumps is related to this. As a consequence of more gas power also the amount of stored CO_2 increases. Nevertheless, it appears that the basic insights are insensitive to the number of typical days. Figure 8 shows the same indicators for different intra-day cluster, all for 24 typical days. Here the influence is considerably larger. Especially the case with no intraday resolution differs considerably from the others.

Figure 9 and Figure 10 shows yearly time series for electricity generation and consumption for different typical days and intraday cluster. Again, the case for no intraday resolution is not a realistic representation as it misses all implications coming from the strong daily variation of photovoltaic generation. In our analysis we use 12 typical days and 3 x 8h clusters for a quick assessment. All results presented in this reported were done with a higher resolution of 36 typical days with 8 x 3h clusters.

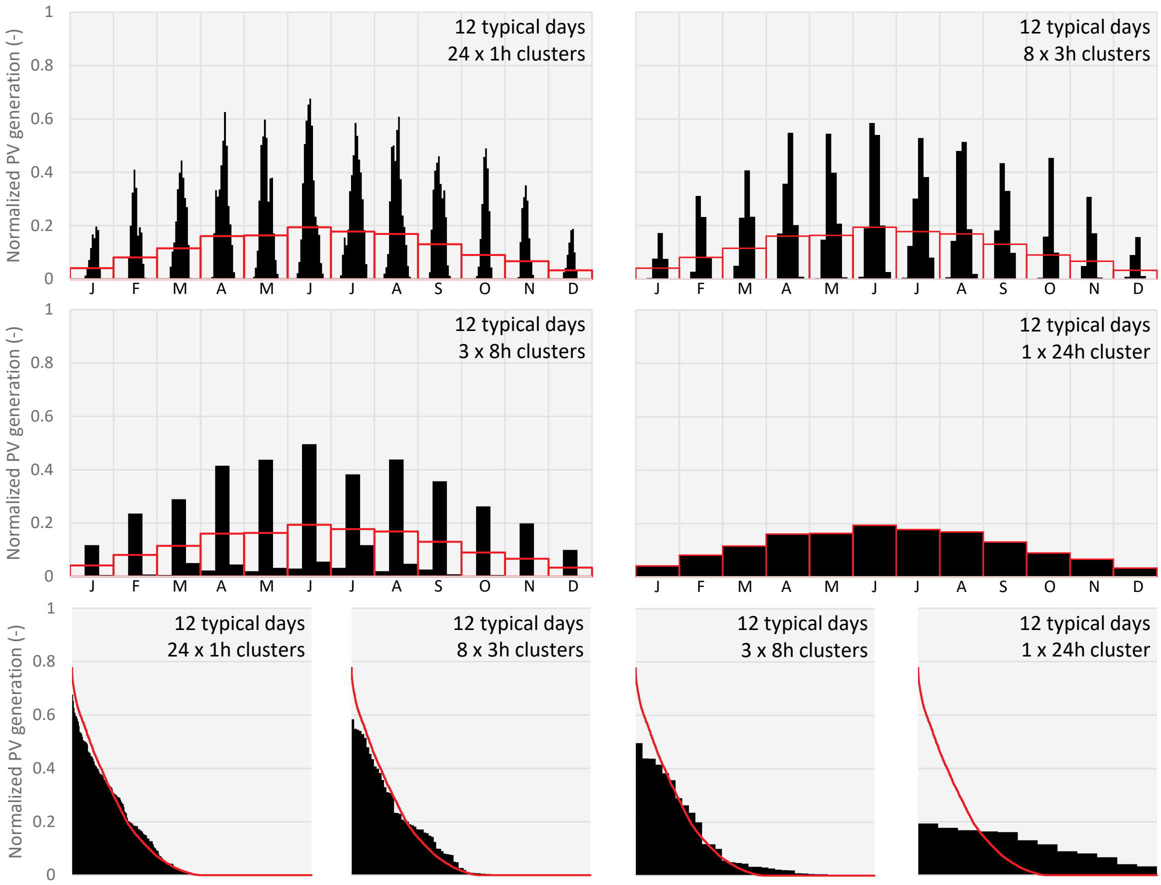

Figure 3: Time series and annual duration curves of photovoltaic generation for 12 typical days.

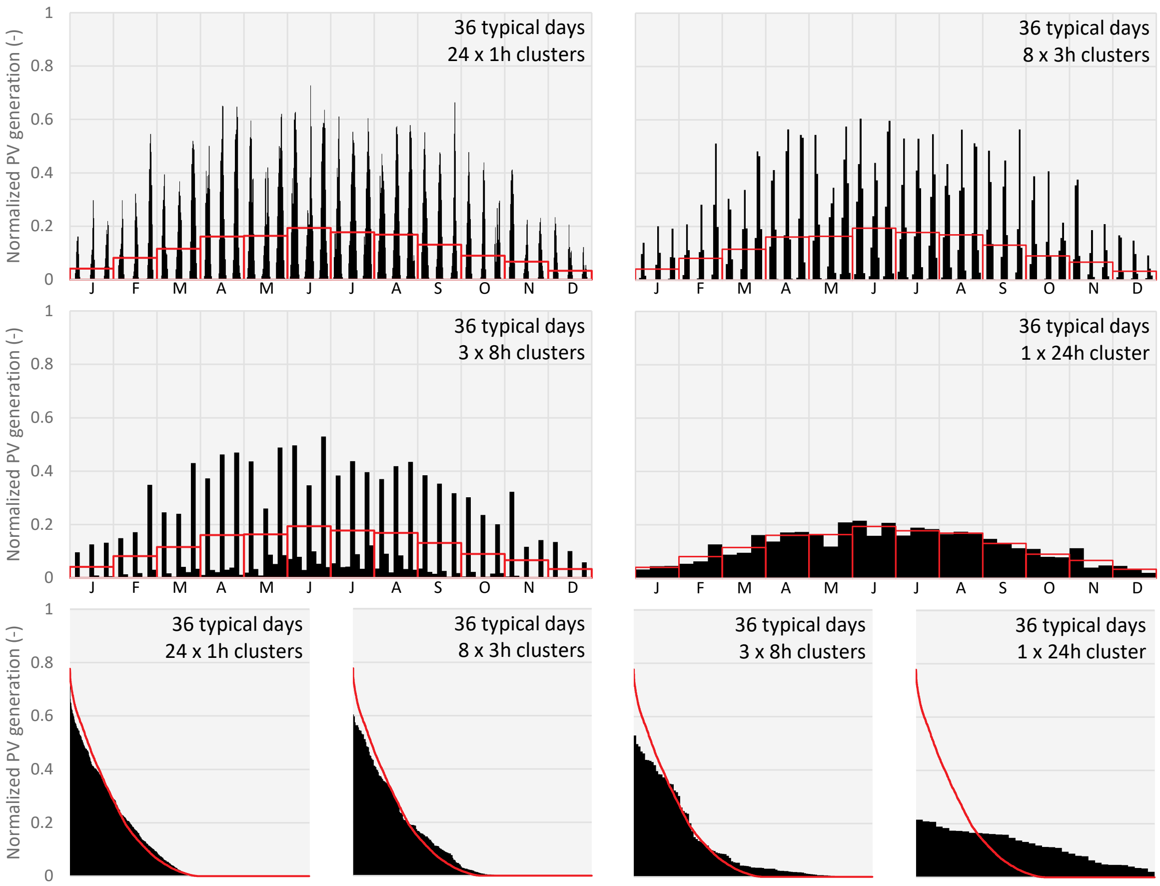

Figure 4: Time series and annual duration curves of photovoltaic generation for 36 typical days.

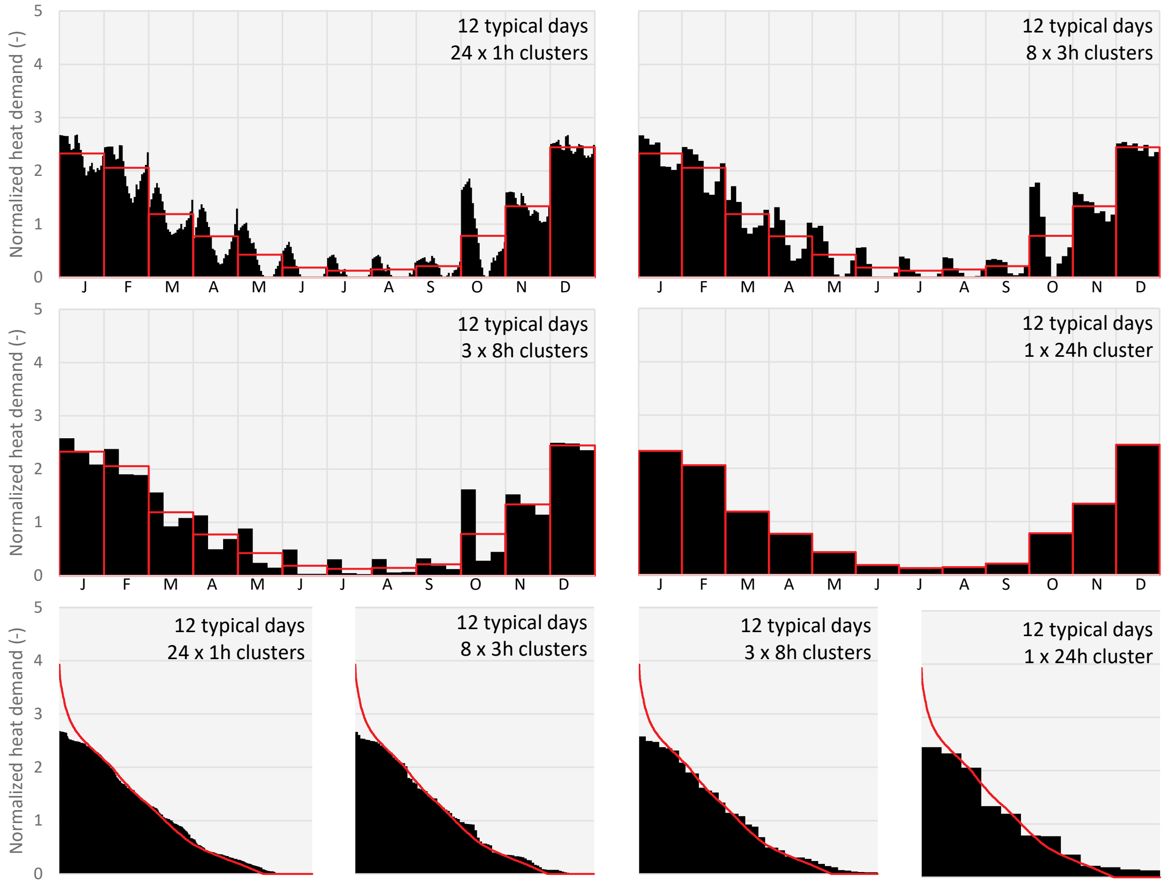

Figure 5: Time series and annual duration curves of heat demand for 12 typical days.

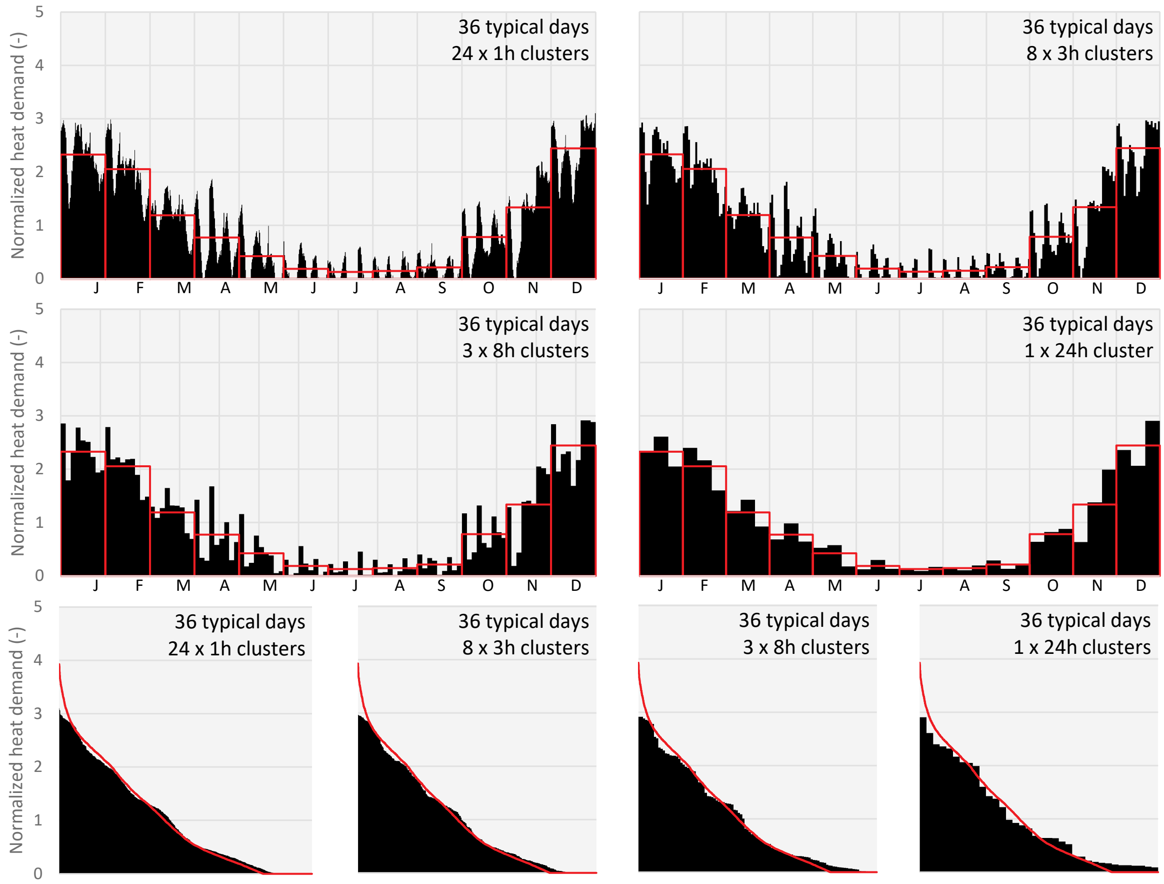

Figure 6: Time series and annual duration curves of heat demand for 36 typical days.

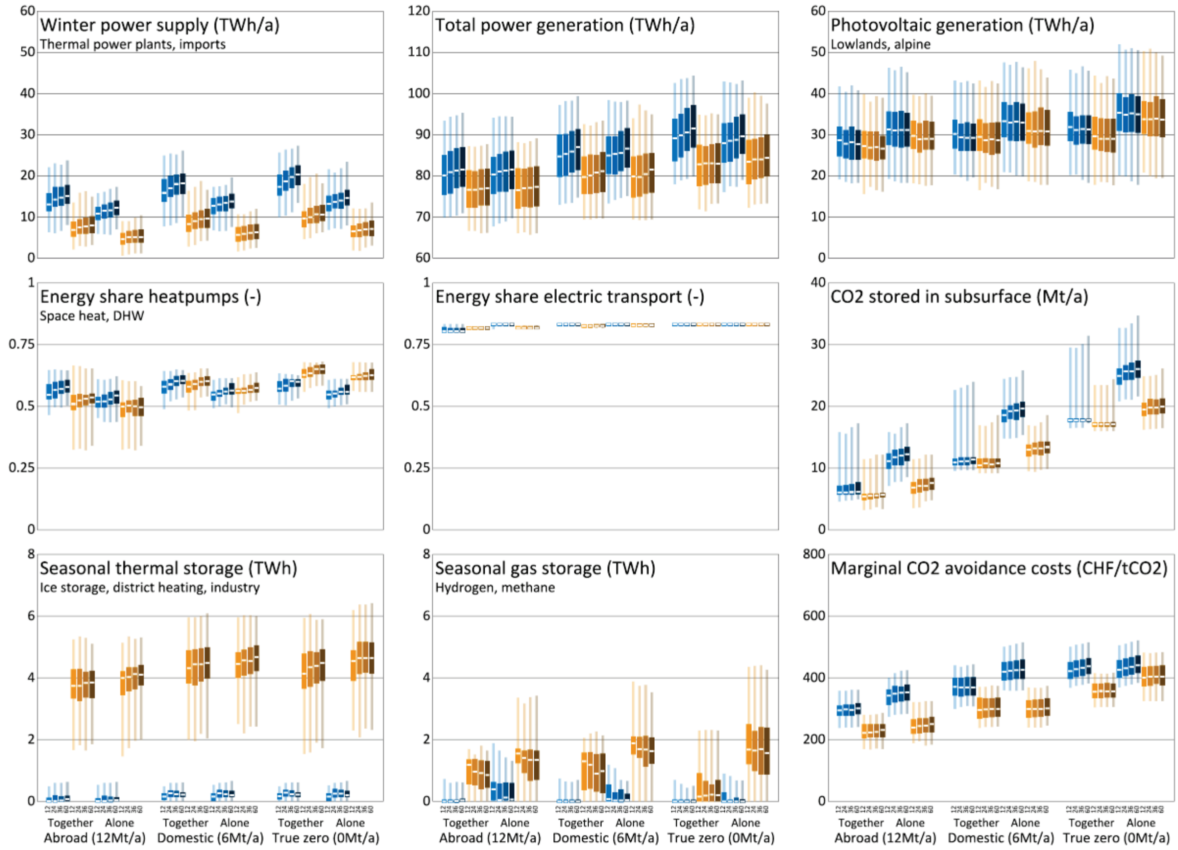

Figure 7: Impact of typical days on selected indicators.

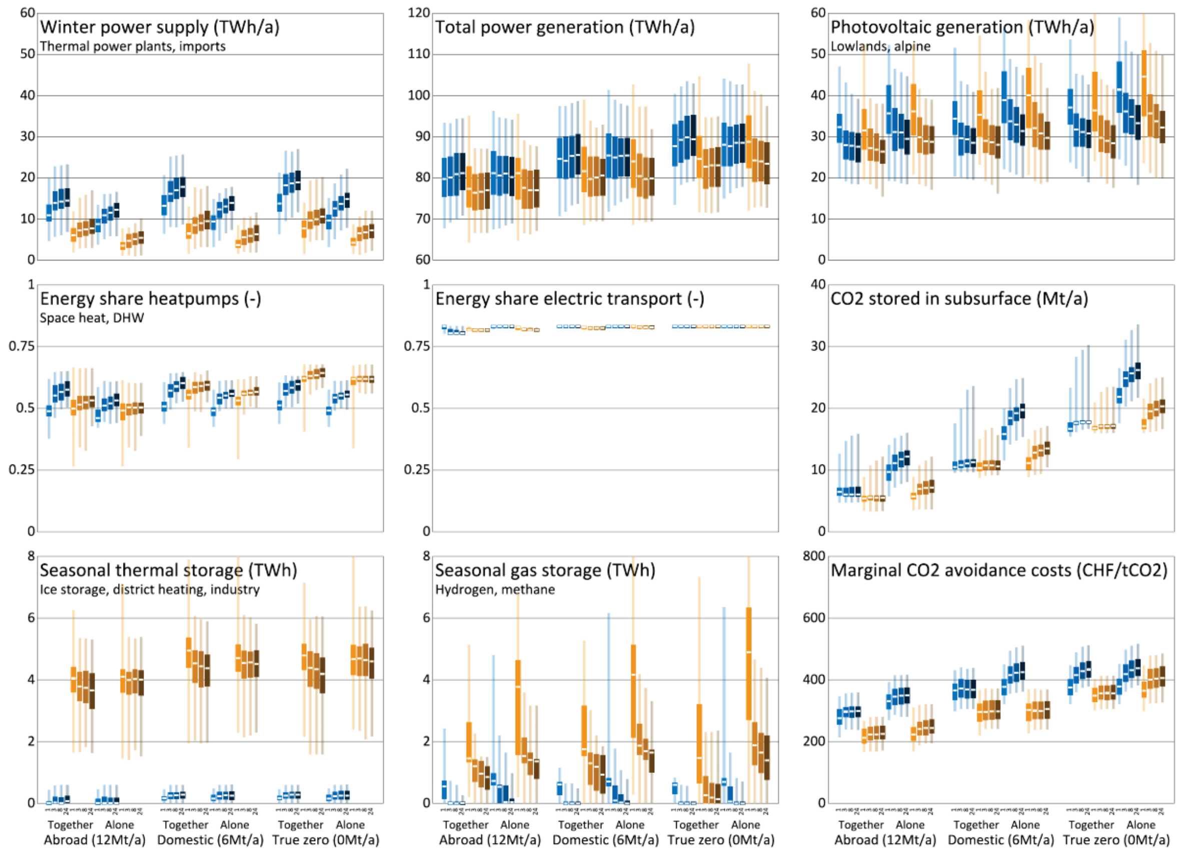

Figure 8: Impact of intra-day clustering on selected indicators.

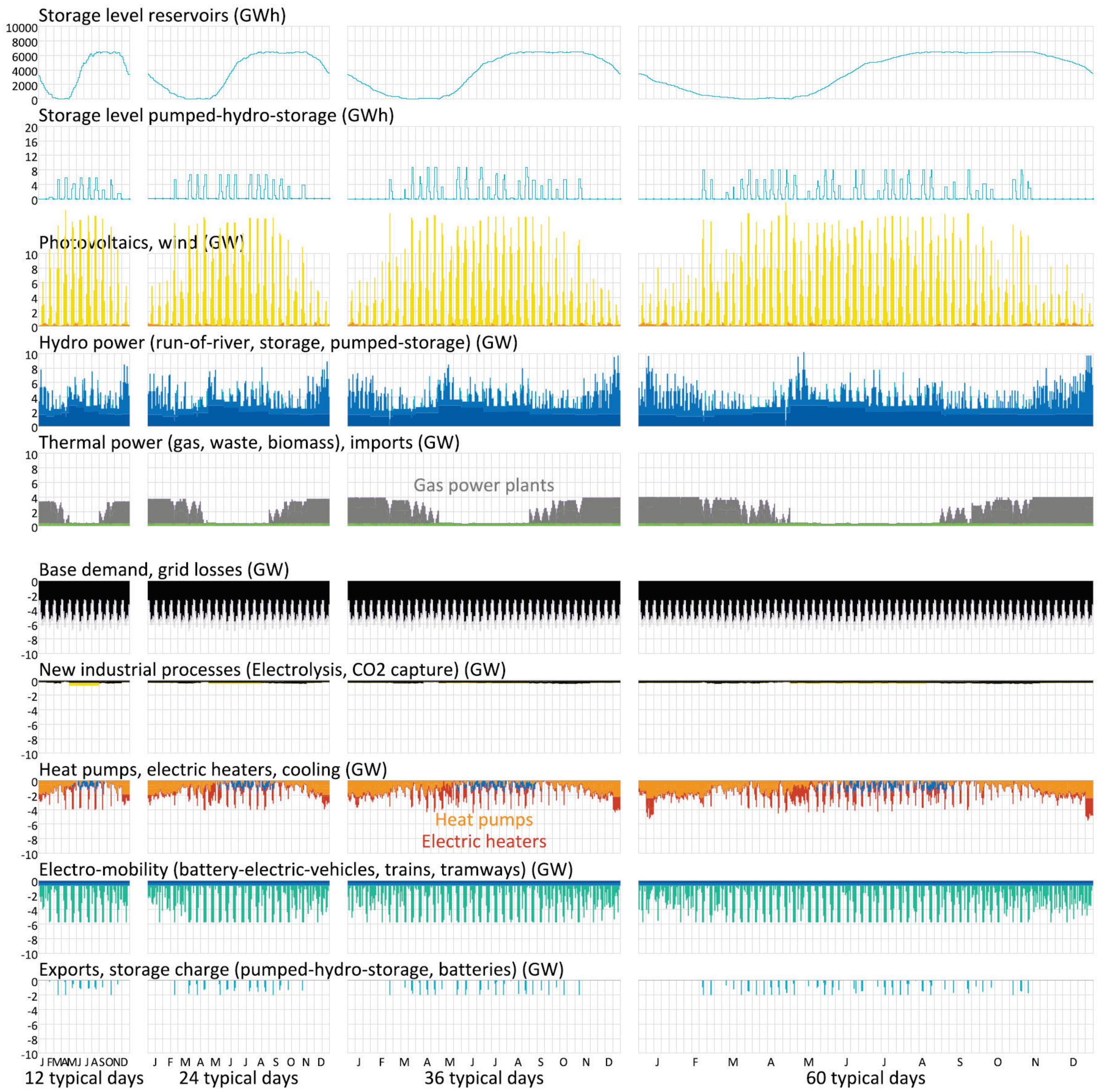

Figure 9: Impact of typical days on electricity production and consumption time series; Conservative/ Alone/Domestic scenario.

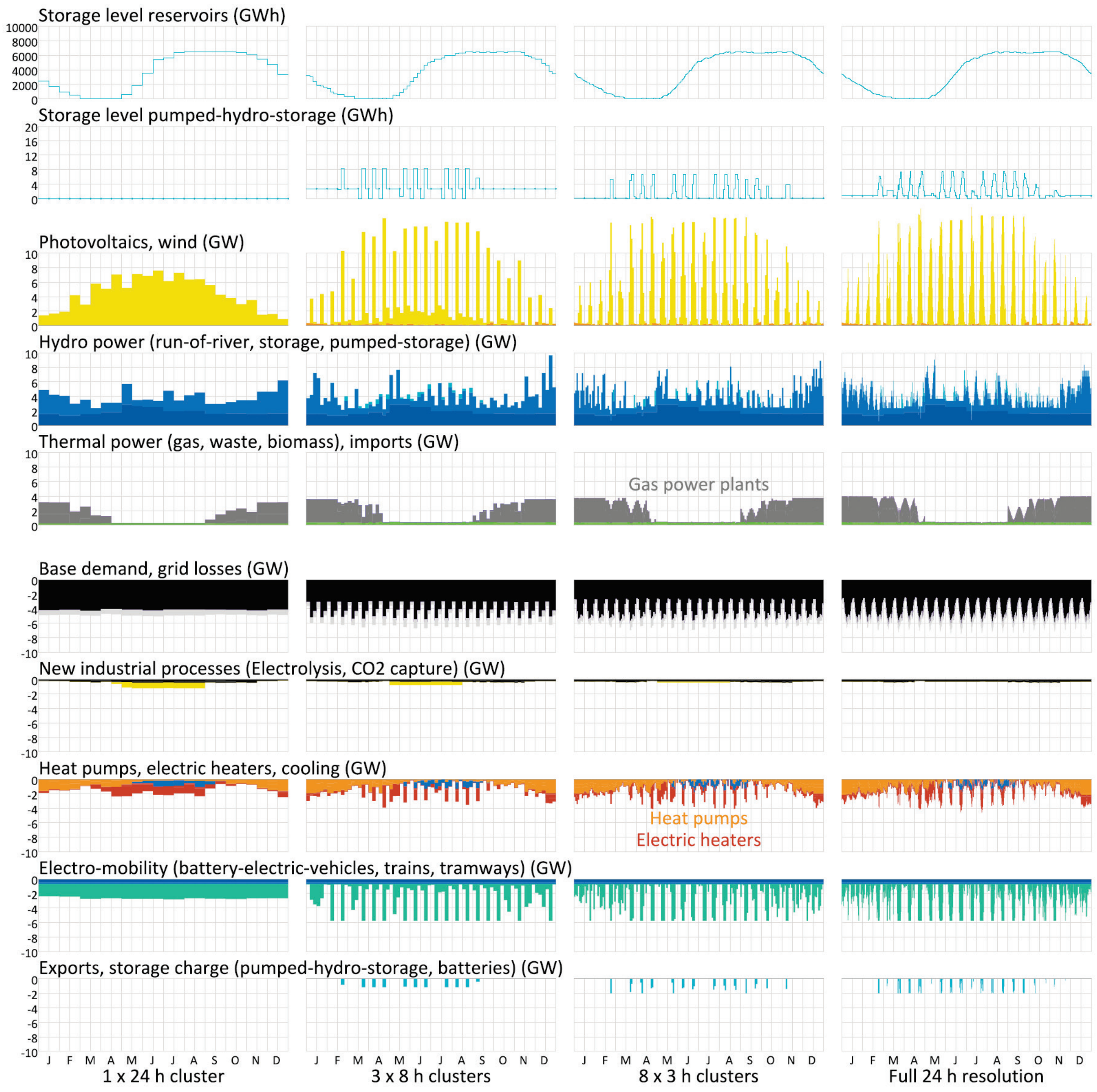

Figure 10: Impact of intraday clustering on electricity production and consumption time series; Conservative/Alone/Domestic scenario.

2.4 Storage

Many layers have the option of storage. The typical day approach requires special care when modelling these devices. We distinguish a seasonal storage that spans across the full year (consisting of 12, 24, 36 or 60 typical days) and a short-term hourly storage that is confined to a single typical day. This restriction is necessary because an exchange of energy between typical days using a short term storage would actually be an exchange between weeks or even months. For seasonal storage we require periodicity over the full year, i.e. the storage level at the beginning and at the end of the year have to be the same. For the short-term storage this periodicity is enforced over a typical day, i.e. the storage level before and after midnight have to be identical. To keep the model simple we consider that this level at midnight is a free variable but has to be the same for each typical day.

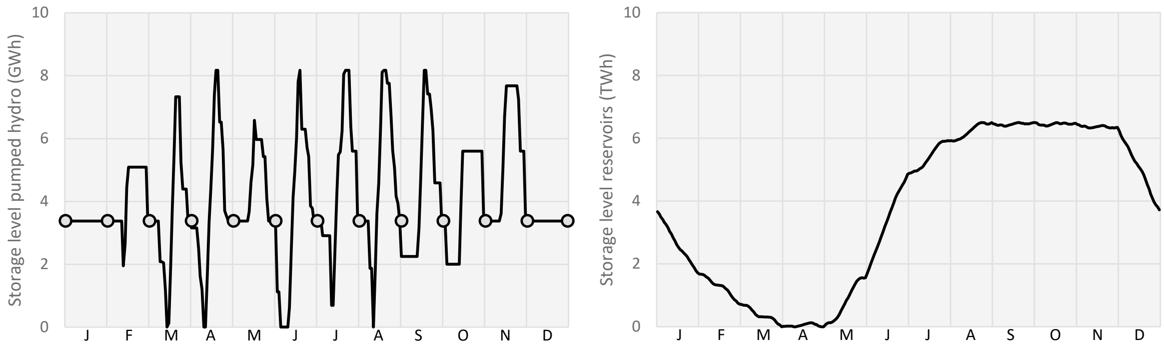

Figure 11: Example for daily storage (left) and seasonal storage (right) for 12 typical days. Periodicity is enforced for the daily storage by having the same storage level at the end of each day.

3 CROSS scenarios

Four scenarios for a net-zero Switzerland in 2050 have been defined within the SWEET-CROSS project [11]. These are generated along two axis, climate policy and energy market integration. We add another dimension by defining a technology conservative and a technology innovative variant, and a stricter climate goal (see Figure 12 and Table 3).

- Climate policy: “Net-zero GHG domestic” is net zero including hard to avoid emissions from agriculture but excluding aviation. “Net-zero GHG – carbon removal abroad” considers the option to compensate up to 6 Mt/a of CO_2-equivalent emissions outside Switzerland. We add a third variant “Real zero” which considers also the emissions from aviation.
- Energy market integration: SES-ETH does not explicitly model the energy system outside Switzerland. Energy carriers like electricity, methane or hydrogen can be imported at a certain price. The two variants “High integration” and “Low integration” are defined.
- Technology innovative/conservative: These variants are distinguished by the willingness to adopt new technologies or to find compromises with other public goods such as landscape preservation. Examples are alpine photovoltaics, the increase of hydro reservoir volumes or geothermal energy.

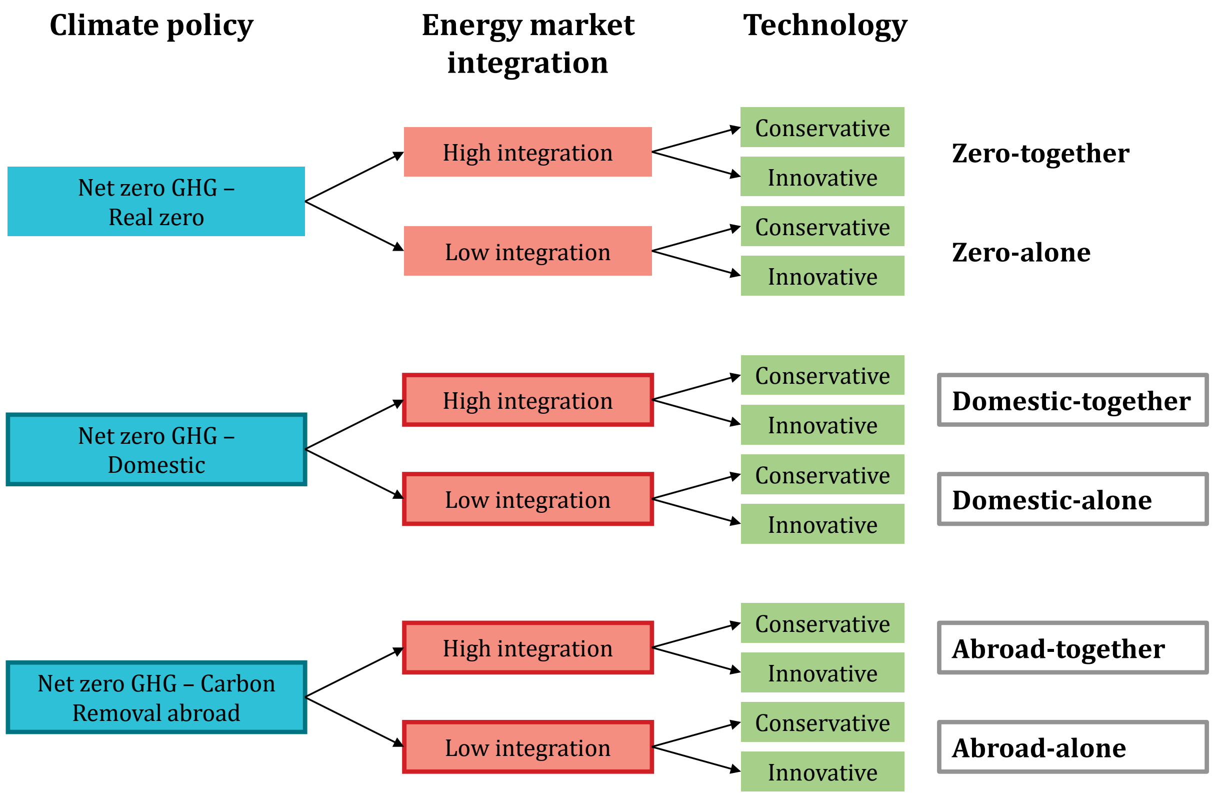

Figure 12: Basic scenarios for CROSS.

Table 3: Key numbers for scenario variants

Climate policy	Real zero	Domestic	Abroad
Target for SES-ETH	0 Mt_{CO2eq}/a	+6 Mt_{CO2eq}/a	+12 Mt_{CO2eq}/a

Market integration	High integration	Low integration
Electricity imports	Unlimited at 130-170 CHF/MWh	None
Methane imports	Unlimited at 30-60 CHF/MWh	
Hydrogen imports	< 40 PJ/a at 160 CHF/MWh	None
Biogas imports	< 44 PJ/a at 100 CHF/MWh	None
Biofuel imports	< 5 PJ/a at 200 CHF/MWh	None

Technology	Innovative	Conservative
Hydro power	< 37.1 TWh/a	< 33.6 TWh/a
Storage reservoirs	< 6.5 TWh	< 8.5 TWh
Wood resource	< 19.3 TWh/a	< 15.6 TWh/a
Wind power	< 2.14 GW	< 0.85 GW
Alpine photovoltaic	< 4 GW	No
Seasonal thermal energy storage	Yes	No
H2 cavern storage	Yes	No
Centralized manure digestion	Yes	No
Hydrothermal conversion of digestate	Yes	No

As Table 3 shows, there are actually three climate goals ranging from +12 Mt_{CO2}/a down to 0 Mt_{CO2}/a. These numbers include aviation which accounts for approx. 6 Mt_{CO2}/a. The question remains, which is the “correct net-zero target”. The answer is not straightforward. The Real Zero scenario enforces either the production of sustainable aviation fuels (SAF) in Switzerland or at least the compensation by negative emissions. Recent results from the VADER project [10] indicate that the first option is not realistic, simply because Switzerland lacks the renewable resources (biomass, PV, wind) to produce SAF domestically. For the second option only direct air capture (DAC) is able to deliver the amount of negative emissions, all other biogenic options are already exhausted to get even down to +6 Mt_{CO2}/a. Probably it is more reasonable to either import SAF or to compensate the use of fossil kerosene by DAC in locations that are more favorable than Switzerland. This could be especially in proximity of storage sites where ideally also low grade heat is available for the DAC process. We therefore consider the Real Zero scenario as an extreme benchmark which may become relevant if emissions have to go below zero in the second half of the 21st century.

Following the argument that Switzerland may be able to import SAFs by the middle of the century, the Domestic climate scenario at +6 Mt_{CO2}/a becomes actually the aforementioned “correct net-zero target”. The Abroad scenario assumes that 6 Mt_{CO2}/a can be compensated abroad, allowing Switzerland to still emit +12 Mt_{CO2}/a. We consider this scenario because it allows to better understand the steps necessary to reach the Domestic scenario.

All assumptions on technology costs and efficiency, resource availability and demand have been documented in a recent study, they can be found in Section 3.3 of the final report [10].

4 Configuration of a net-zero energy system in 2050

Based on the model described in Section 2 and the scenarios from Section 3 we can study the characteristics of future net-zero energy systems. The purpose is to understand which of these characteristics are stable with regards to the uncertainty of many drivers. This section considers the base scenarios from Section 3, namely the three climate targets (Abroad – 12 Mt_{CO2}/a; Domestic – 6 Mt_{CO2}/a; Zero – 0 Mt_{CO2}/a), the two levels of integration with the surrounding countries (Together – good integration; Alone – poor integration), and the two variants concerning our willingness to adapt new technologies (Conservative, Innovative). In order to better see trends we added two intermediate CO_2 emission targets at 3 and 9 Mt_{CO2}/a. On top of these 20 base scenarios, we consider the uncertainty of future population development, climate, technology and resource costs, etc. by a Monte Carlo analysis.

Results are presented in the coming subsections. The last subsection will summarize the insights that are relevant for the technology development in SWEET-DeCarbCH and also highlight the necessary model improvements that will be implemented based on the insights from the other workpackages.

4.1 Electricity production and consumption

Figure 13 displays the mix of electricity generation technologies for the base scenarios. The most notable aspect is the total generation that falls roughly in the range of 70-90 TWh/a. This is in average one third higher than today's typical value of 60 TWh/a. The bulk of electricity stems from two sources, hydro power and photovoltaic. The next category is methane fired thermal power plants and/or net electricity imports. Here the share varies strongly depending on the integration with the surrounding countries. In the Alone scenarios, no net electricity imports are allowed, and the generation from gas turbines is higher. Finally, some generation comes from additional thermal power plants that burn either solid fuels like waste and wood, hydrogen or diesel. The overall electricity generation is higher for the conservative scenarios, mainly due to lower non-electrical resources such as wood or geothermal energy..

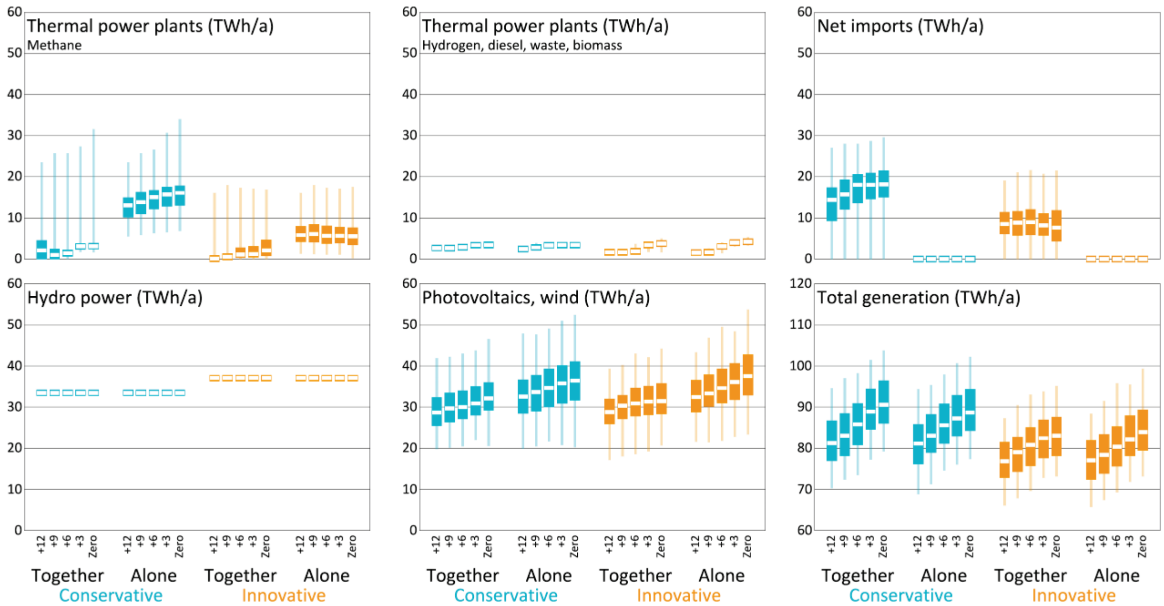

Figure 13: Electricity generation for base scenarios.

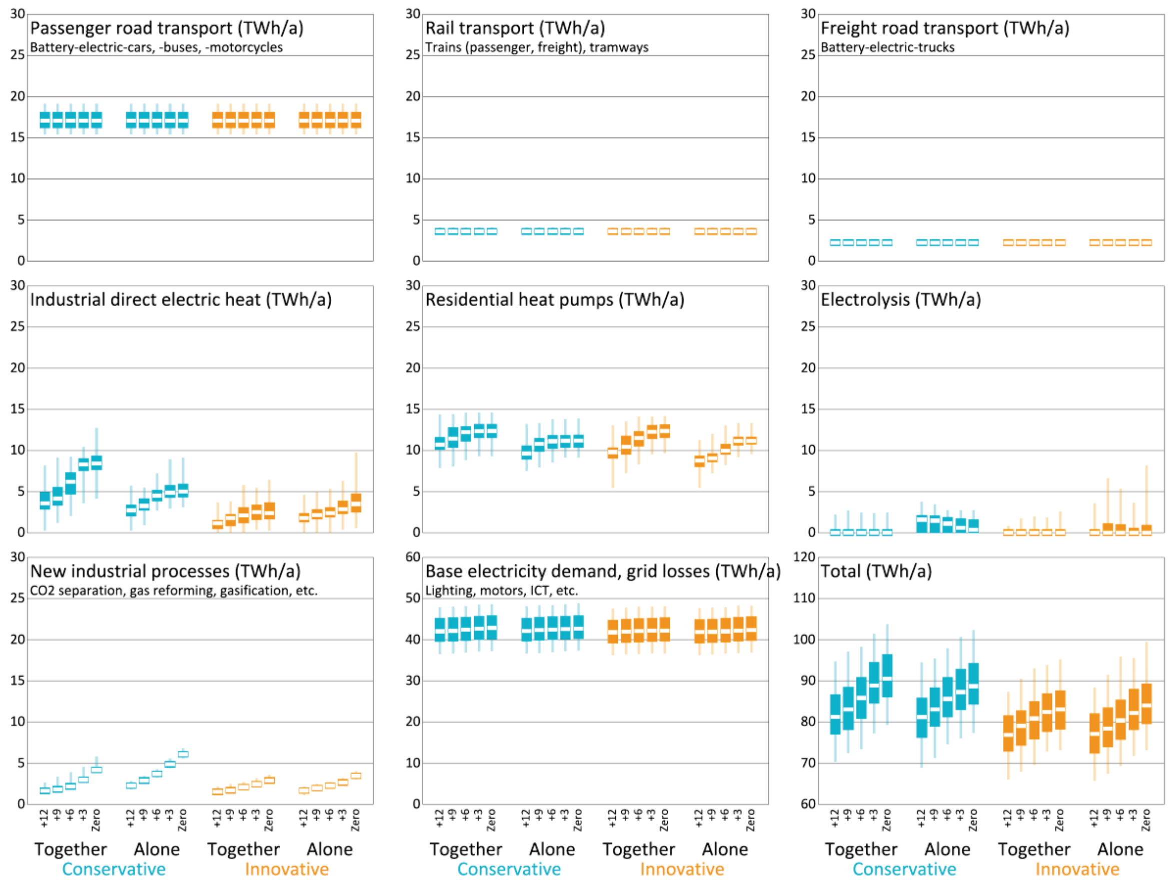

Figure 14: Electricity consumptions for base scenarios.

Figure 14 display the electricity consumption for various categories. The largest share is the base consumption for lighting, motors, ICT, etc. Here we group all uses that can only be satisfied by electricity. The provision of mobility and heating services does not fall into this category because in principle these services can be provided by alternative means. The second largest category of electricity consumption is the transport sector, which in turn is dominated by private mobility with battery electric vehicles. Heat pumps for the provision of space heat and domestic hot water and direct heaters for industrial process heat are the next group of consumers. Last but not least, a number of new industrial processes such as CCS require an amount of electricity that increases with the more ambitious climate goals. Electrolysis play only a minor role for the base scenarios.

4.2 Space heat and domestic hot water

The next important demand category is space heat and domestic hot water. As explained in Section 2.2, the demand is split into a number of archetypes for district heating networks and single/multi family houses. These archetypes include a large variety of technologies, e.g. heat pumps, burners, combined heat & power plants. Figure 15 categorizes these by the source. It is evident that heat pumps (air, ground, water) are the dominant technology. However, since we assume that not all buildings are suitable for a heat pump, a mix of combustion technologies appears (either boilers or CHP plants), that use gaseous or liquid fuels, waste and wood in larger CHP plants or domestic pellet boilers. Also solar thermal makes a contribution, mostly to save other resources like wood or methane in the summer months.

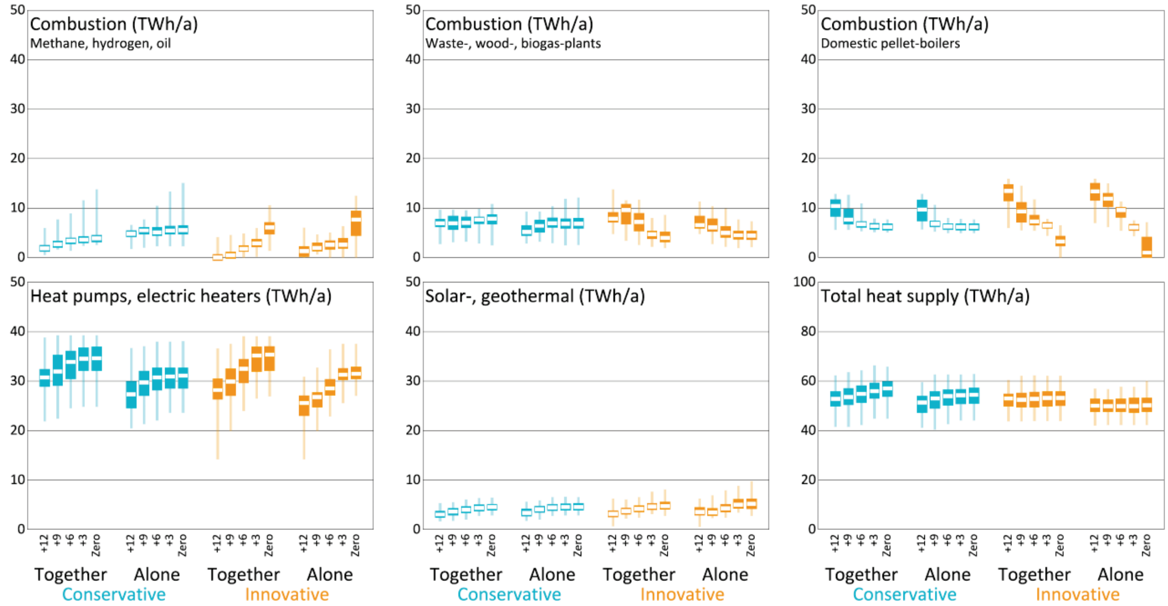

Figure 15: Space heat and domestic hot water supply for base scenarios.

4.3 Industrial process heat

As explained in Section 2.2 we split industrial process heat into two categories, namely medium temperature (approx. 80-150 °C) that can be served by geothermal or solar thermal sources, and by CHP plants with steam extraction or back pressure turbines, and high temperature (> 150 °C) that can be supplied by direct combustion or electric heating.

Figure 16 shows the sources of medium temperature process heat. In all cases, waste-to-energy plants have a significant share. A major difference between the Conservative and Innovative scenarios comes from the availability of geothermal energy in the latter. The lack of this resource in the Conservative scenarios is compensated by more heat from gas or biomass CHP plants and by a higher solar thermal generation. Figure 18 shows the demand for medium temperature process heat. Remarkably, the base demand for industrial processes is only a part of the demand, an even larger share comes from the various CO_2 separation processes that are needed to achieve the net-zero objectives. As a consequence, this part increases strongly for more ambitious climate targets.

The supply of high temperature process heat is shown in Figure 17. A large share comes again from waste combustion, mainly in cement plants. Other contributions are the combustion of methane or diesel and direct electrical heating. For more ambitious climate targets, the share of the latter increases. Hydrogen combustion plays only a minor role.

This modelling of process heat, especially the distinction in medium and high temperature is very simplistic and will be a topic for further improvement in the coming year. Important will be especially a better understanding of the actual temperature levels needed in industry, that is elaborated in WP4 of SWEET-DeCarbCH.

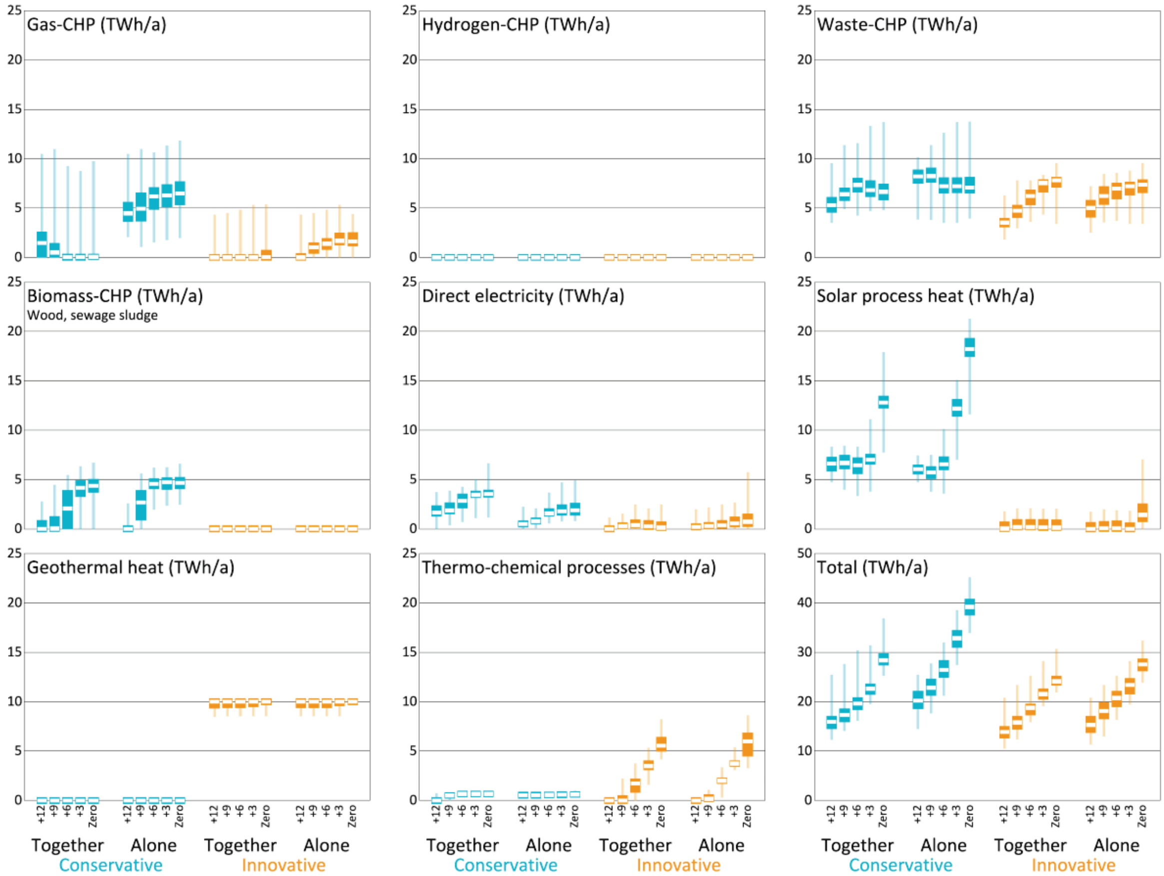

Figure 16: Supply of medium temperature industrial process heat.

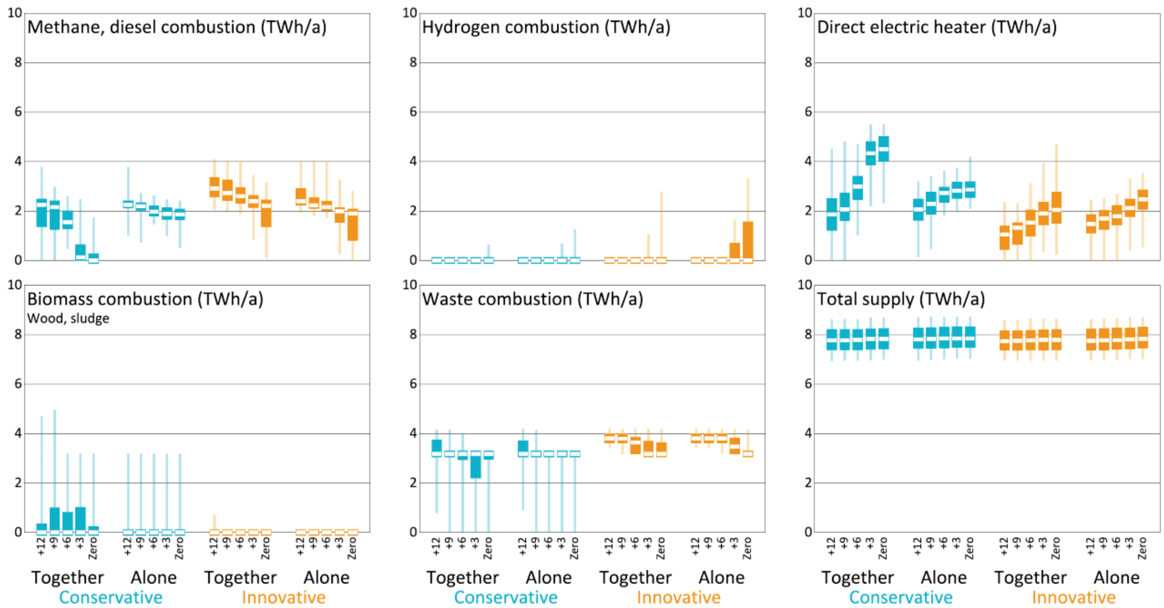

Figure 17: Supply of high temperature industrial process heat.

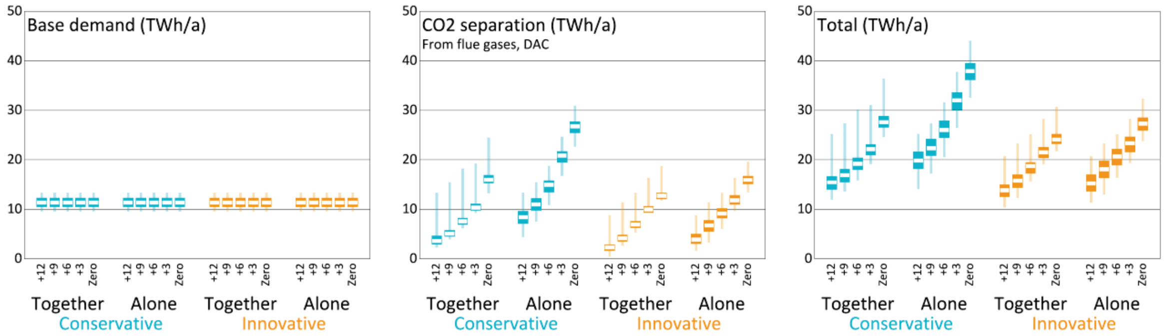

Figure 18: Demand for medium temperature industrial process heat.

4.4 Production and consumption of chemical energy carriers

In today's world, chemical energy carriers are almost exclusively imported from fossil sources. It is often believed that such energy carriers will largely be produced from electricity, via electrolysis and subsequent synthesis steps to produce synthetic gases or liquid fuels. Our models allows to shed some light on these developments. We take a separate look on generation and demand of hydrogen, methane and liquid fuels (diesel and kerosene).

Figure 19 and Figure 20 shows the supply and demand for hydrogen, respectively. It can be seen that the supply is dominated by thermochemical processes such as steam methane reforming (with CCS – blue hydrogen), and wood gasification with water-gas-shift. The latter is only available in the Innovative scenarios. Electrolysis plays only a minor part. An explanation can be found by considering the demand for hydrogen. This is mainly for freight mobility, requiring a constant supply throughout the year. Here, a thermochemical process has advantages over electrolysis since it uses an energy input that is available the whole year, allowing to operate at constant rate. These result show that at least under the conditions of the base scenarios, power-to-hydrogen plays a minor role, and power-to-hydrogen-to-power is not relevant at all.

Figure 21 and Figure 22 show the supply and use of methane. Supply is dominated by imports, especially in the Conservative scenarios. Domestic generation by anaerobic digestion amounts to 2-5 TWh/a depending on whether we assume a proper use of agricultural biomass in facilities that are connected to a gas grid. Especially in the Innovative scenarios, the fraction of biogenic methane can reach 40% and more. Methane production through thermochemical routes (including power-to-methane) plays no role. The use of methane is dominated by combined heat and power plants that deliver electricity and heat especially in winter. Methane is also used for hydrogen production through steam methane reforming in the Conservative scenarios.

Finally, liquid fuels (diesel, kerosene) are mostly imported, with some production via gasification and Fischer-Tropsch synthesis for the most ambitious emission targets (Figure 23). Interesting is the production of Diesel via hydrothermal liquefaction of digestate that delivers 4-5 TWh/a. The use of liquid fuels (Figure 24) is dominated by aviation. Diesel is used for freight transport but there is a transition to power generation for the lower emission targets. This is complementary to the switch to hydrogen as fuel for freight transport seen in Figure 20.

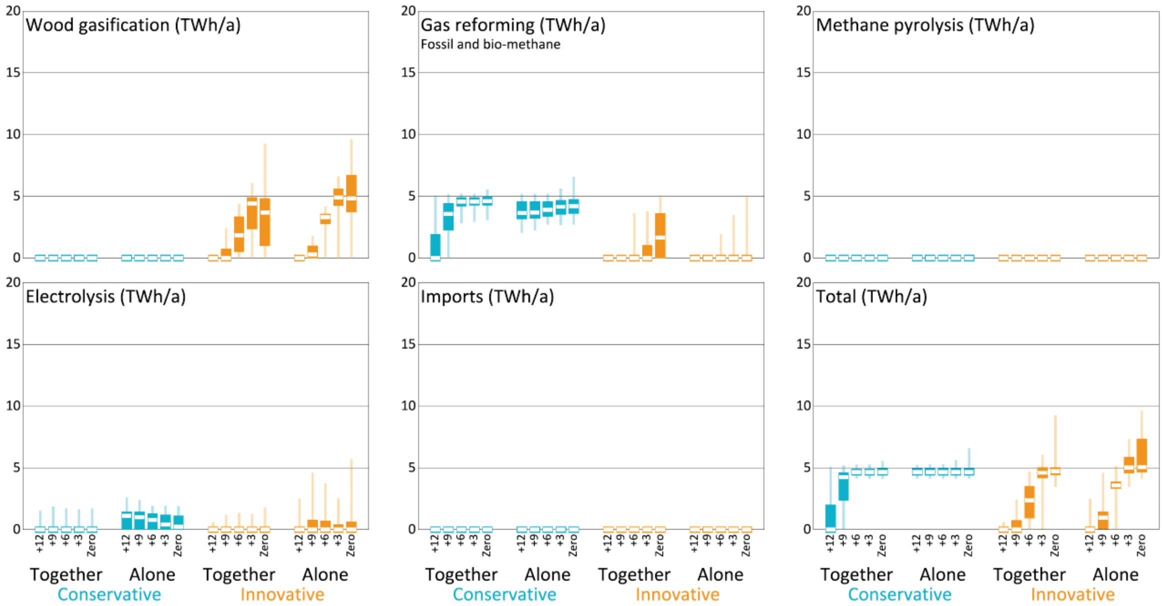

Figure 19: Supply of hydrogen.

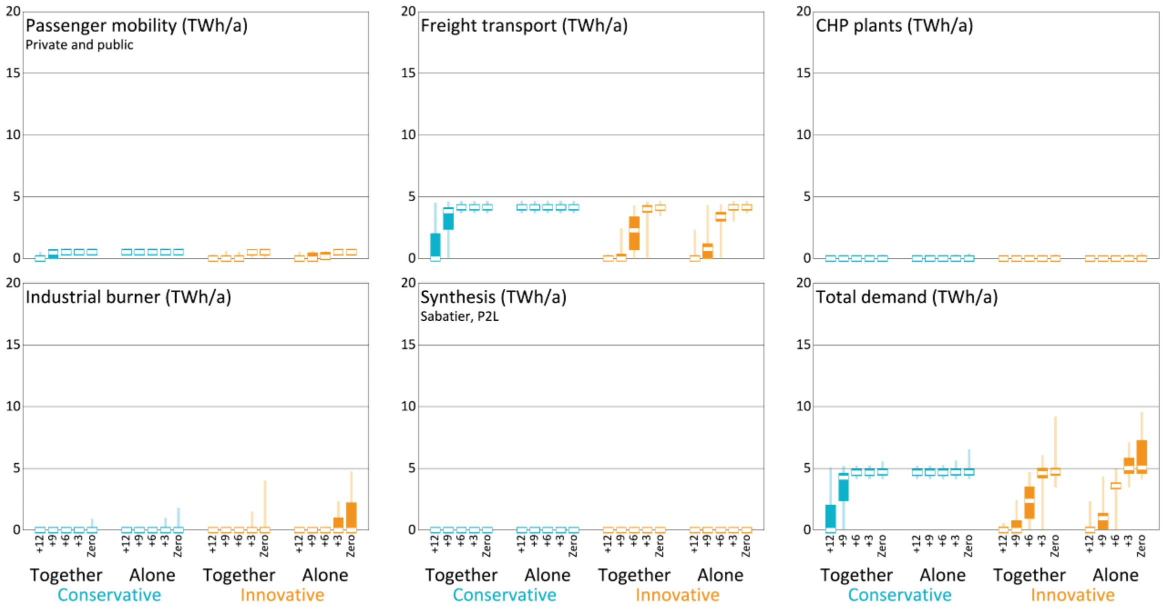

Figure 20: Demand for hydrogen.

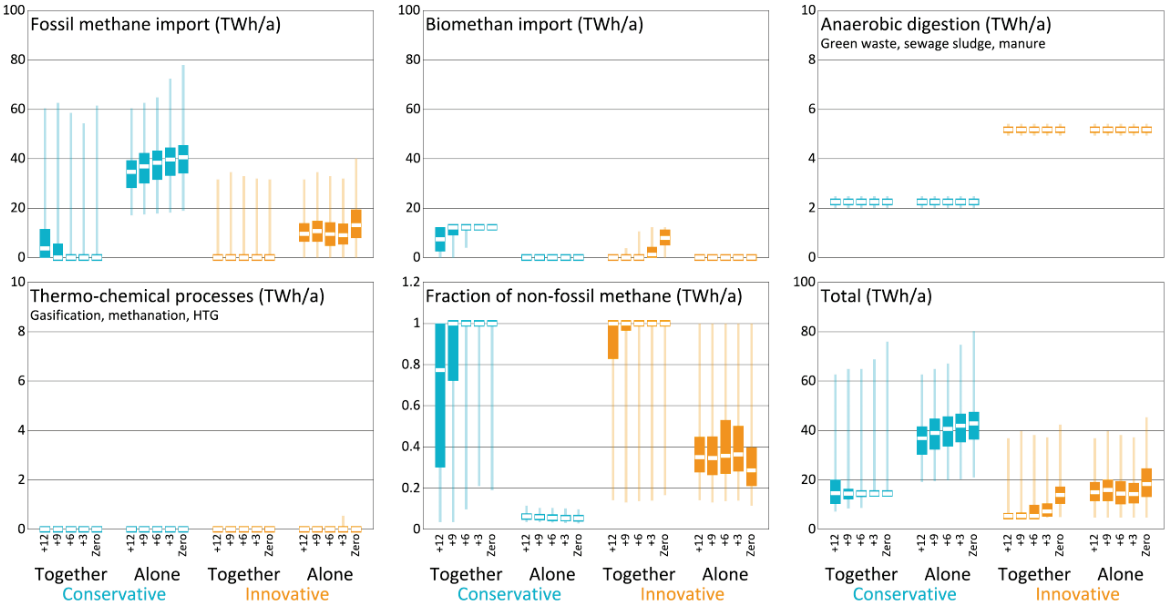

Figure 21: Supply of methane.

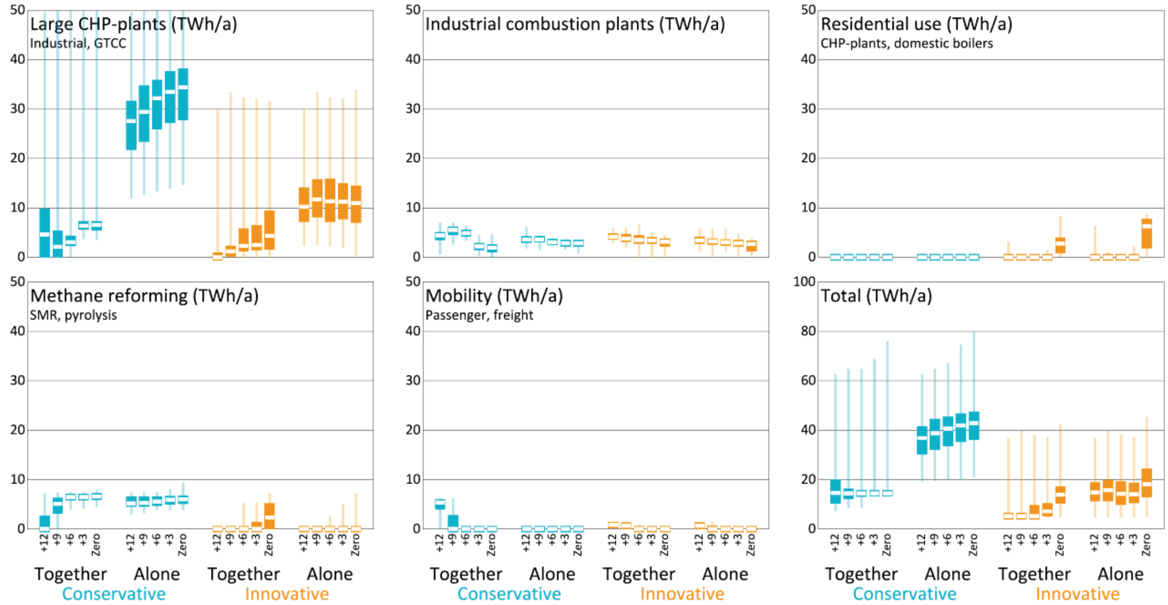

Figure 22: Demand for methane.

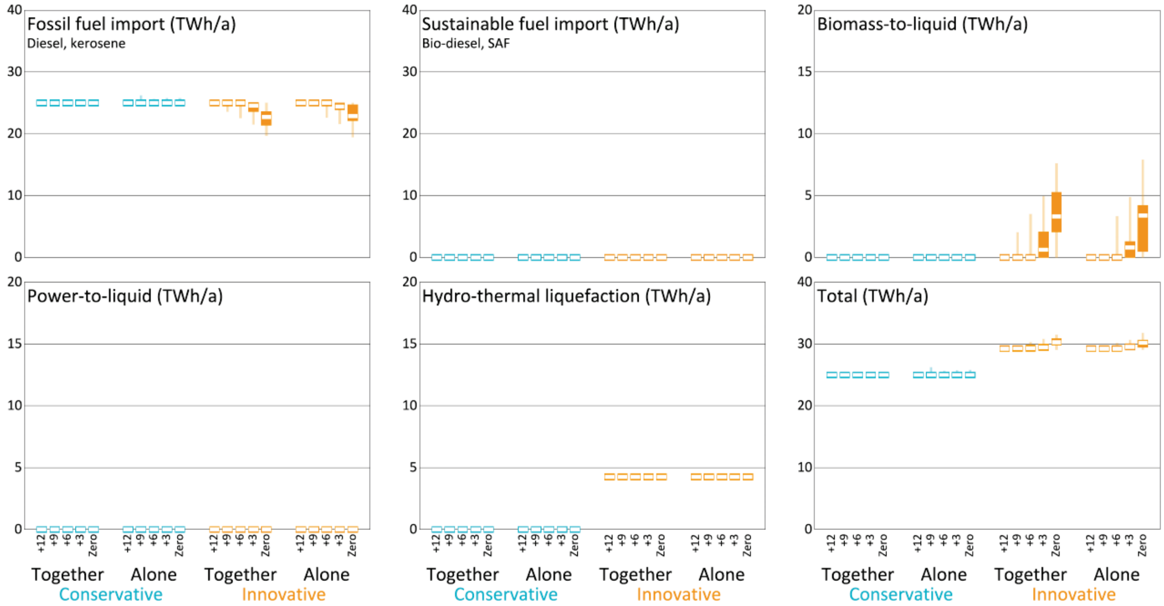

Figure 23: Supply of liquid fuels.

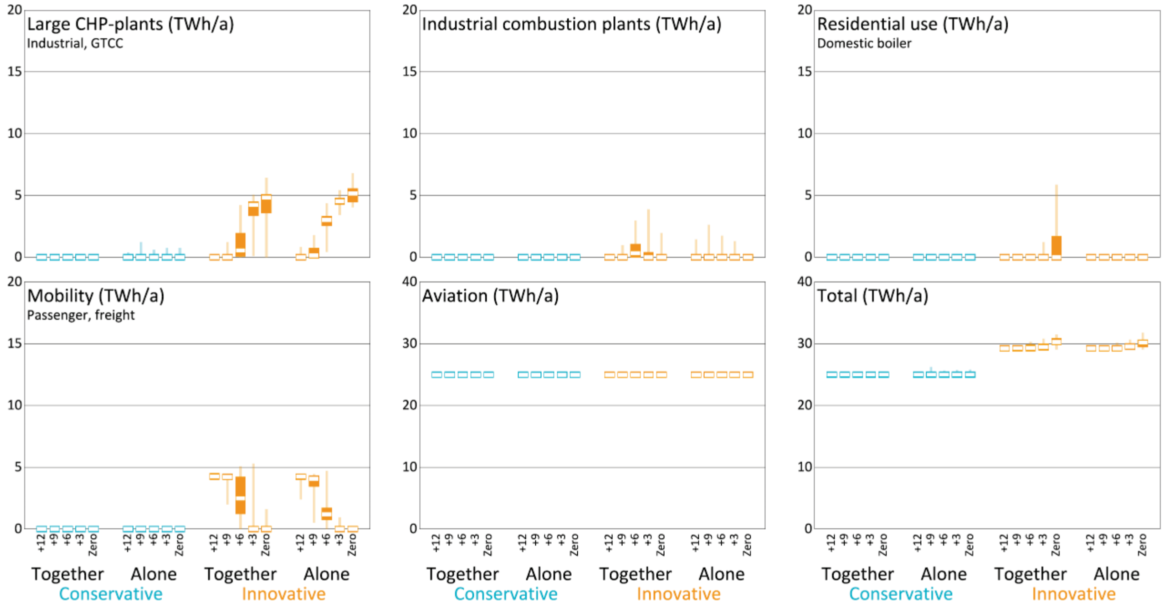

Figure 24: Demand for liquid fuels.

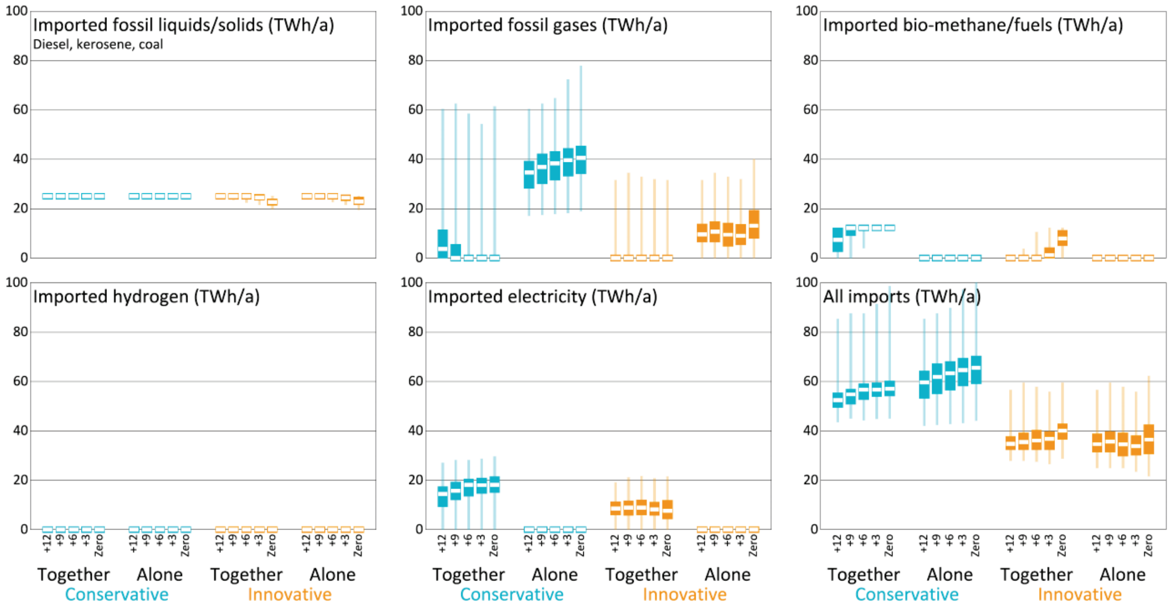

Figure 25: Energy imports.

4.5 Overall energy imports

Switzerland imported in the last years some 120-130 TWh/a of oil products (gasoline, diesel, kerosene) and some 30-35 TWh/a of methane. There is no clear trend concerning the electricity balance, some years Switzerland was a net exporter of a few TWh/a in others a net importer.

Figure 25 shows clearly that energy imports will dramatically decline for the base scenarios. Gasoline and diesel imports go to zero, only kerosene is still imported. Methane imports may stay at a level of today for a Conservative scenario with no electricity imports (Alone). However, these imports can be massively reduced by realizing the measures and technologies that distinguish the Conservative from the Innovative scenarios (geothermal energy, more hydro power, alpine PV, and many more, see Section 3). It should also be noted that the majority of imports are kerosene for aviation, that has no impact on the supply security of our basic needs for electricity, heat and land based mobility.

4.6 Energy flow diagrams

Figure 26 to Figure 29 show the energy flow diagrams for the base scenarios at the Domestic CO_2 target.

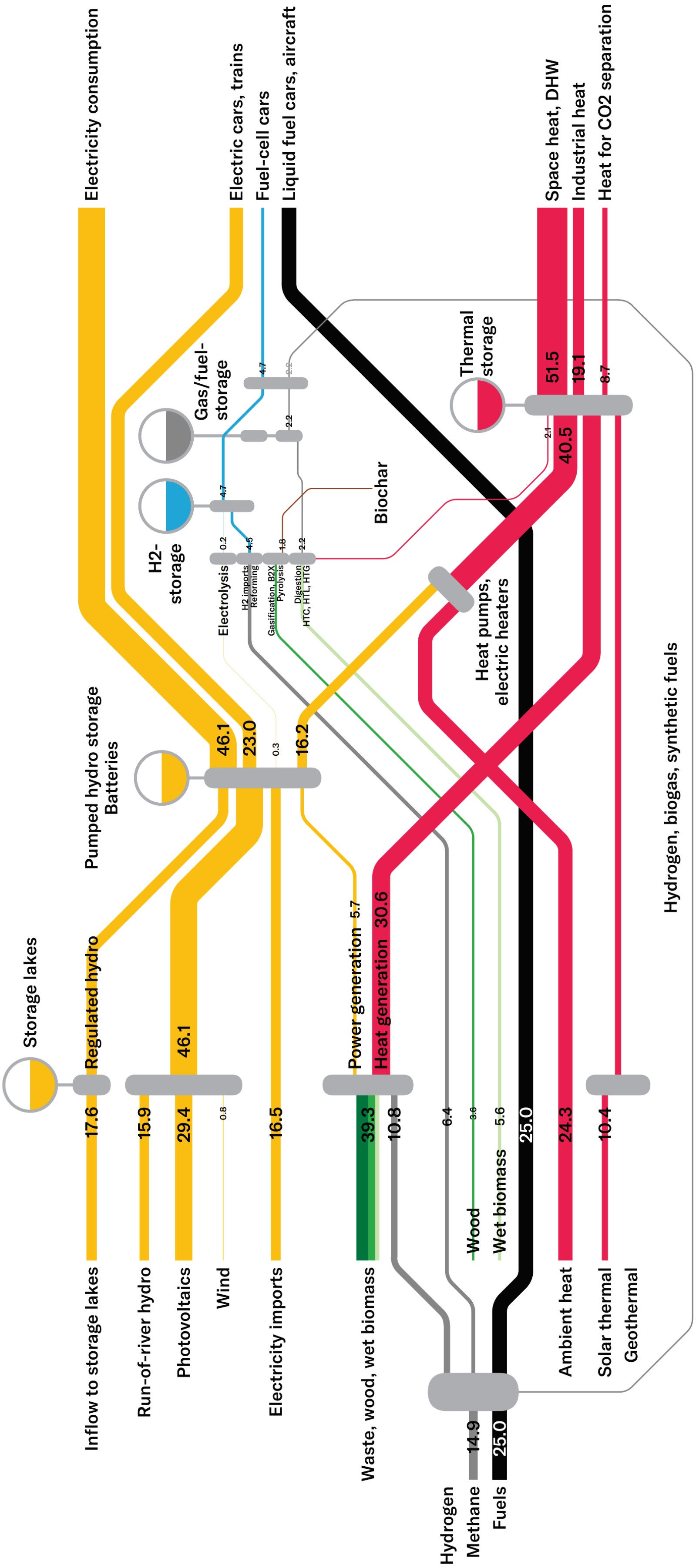

Figure 26: Energy flow diagram for Together / Conservative scenario at 6 Mt_{CO2}/a.

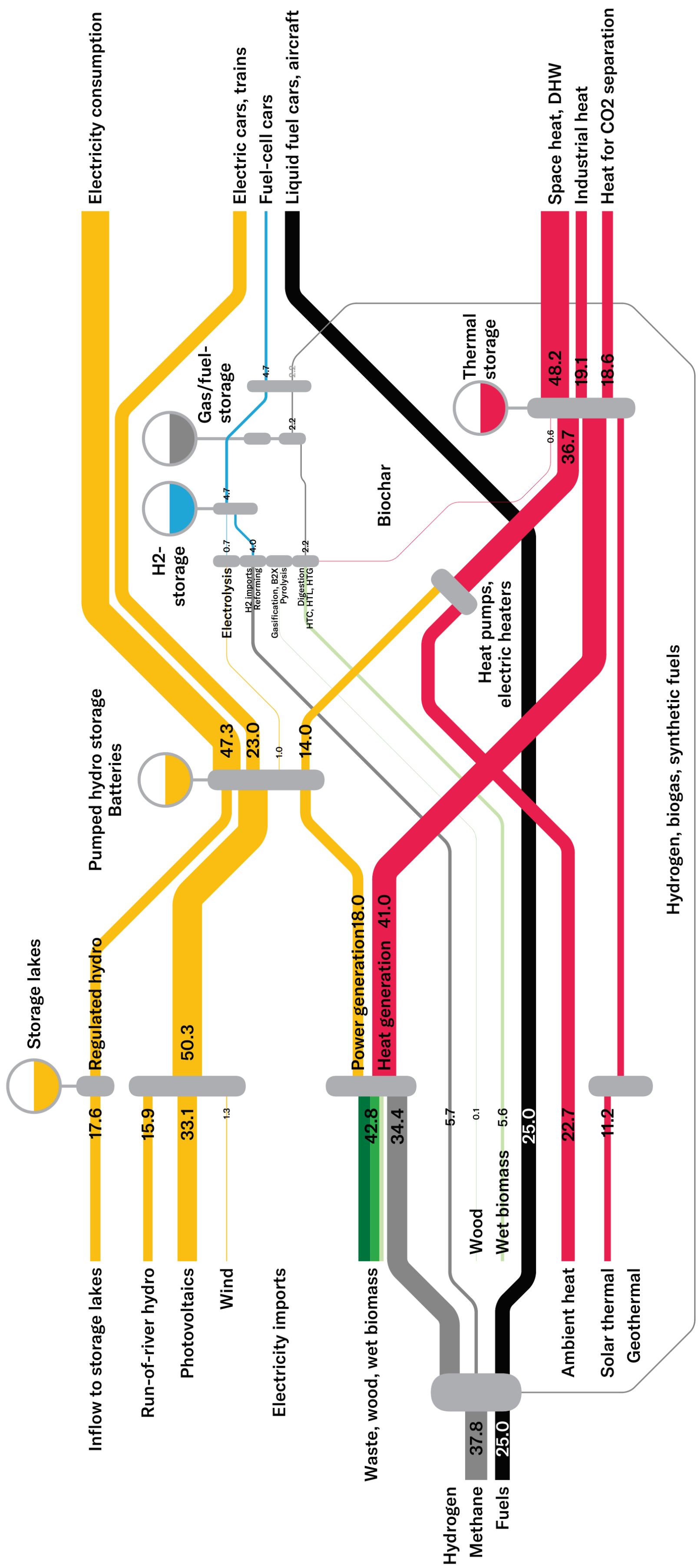

Figure 27: Energy flow diagram for Alone / Conservative scenario at 6 Mt_{CO2}/a

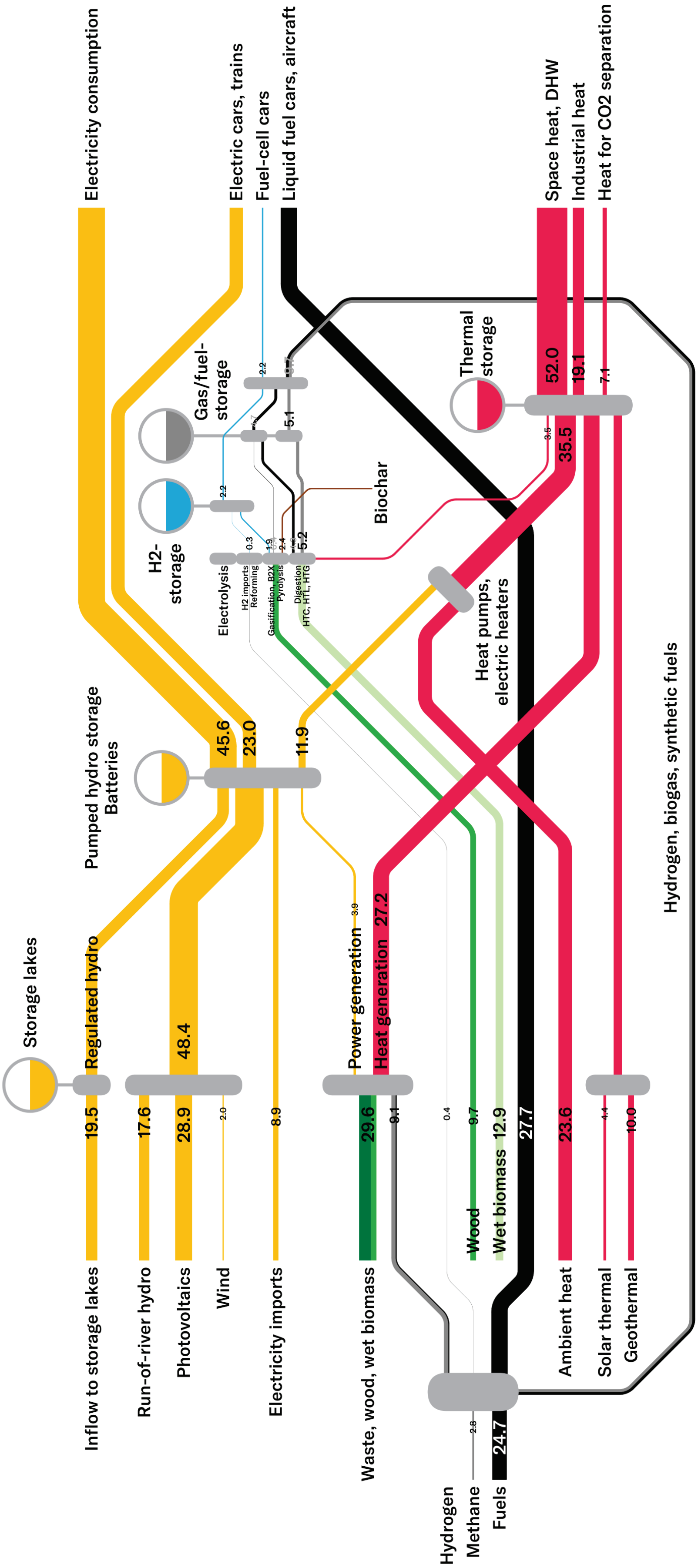

Figure 28: Energy flow diagram for Together / Innovative scenario at 6 Mt_{CO2}/a.

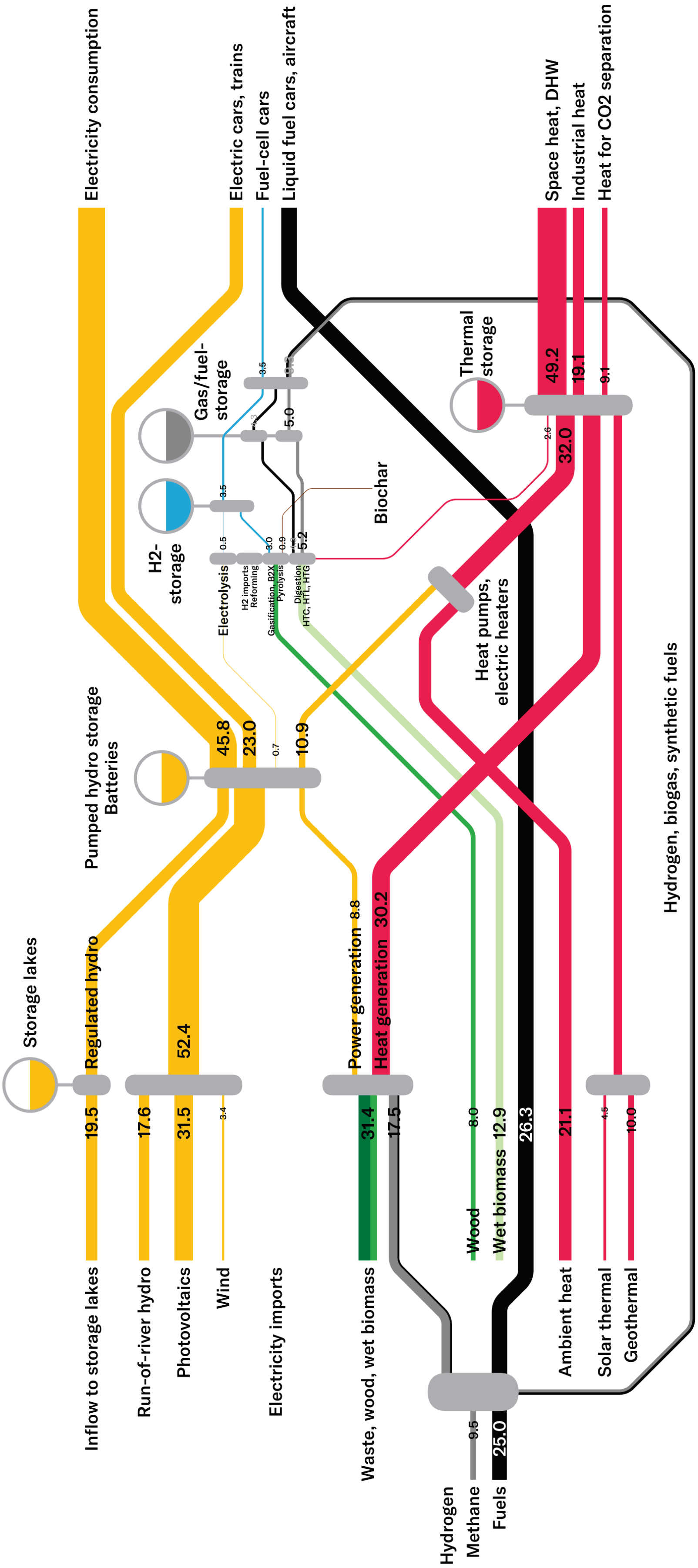

Figure 29: Energy flow diagram for Together / Innovative scenario at 6 Mt_{CO2}/a.

4.7 Interplay of energy streams in time

The previous sub-sections reported energy flows on an annual basis. This does not allow to see what actually happens on the various time scales from hours, to days to seasons. This section shows time series for a scenario that is close to the median of the statistical distributions shown previously. We choose the intermediate climate target (Domestic, 6 Mt_{CO2}/a).

The central element of the future energy system is the production and consumption of electricity. Figure 30 shows the time series using 36 typical days and the 8x3h intraday resolution. Each column represents a base scenario. Two problems need to be solved that are both related to photovoltaics, the daily cycle and the seasonal cycle. In simple terms: there is too much PV at noon and nothing at night, and there is too much in summer and not enough in winter.

The overproduction in summer at noon leads to the common misconception that the electricity cannot be used and is therefore for free (or has even a negative price). This is not the case, different technologies work together to "digest" this overproduction. The first is the simplest, a curtailment of the peaks (1). Our results show that approx. 5% of photovoltaic generation is rejected this way. This has obviously a financial implication since the investment is not fully utilized. However, any additional technology that would use these peaks could operate only 500-1000 hours per year and that is often not enough for a cost effective operation.

The second "line of defense" is the flexibility of storage hydro power plants (2). They follow photovoltaic production in its daily cycling by operating mostly during the night and run on a minimal load during the day. Both the cycling and the minimal load have to be carefully tuned to minimize negative impacts on the aquatic flora and fauna. This operation is supported by batteries and pumped hydro power plants that fill their upper reservoirs during the day and empty it during the night (3). In our simulation PHS is not fully exploited and could therefore take over the role of storage hydro in case the aforementioned flexibility has to be reduced.

What is now left in overproduction is taken by flexible charging stations for battery electric vehicles (4). Here we make a simple assumptions: the results show that private mobility has to be largely electrified to achieve our climate targets. This means that some 4-5 mio BEV will be operating in Switzerland in 2050. Assuming a very modest charging power of 10 kW per vehicle gives a total charging power of 40-50 GW if all vehicles were connected to the grid. We take 10% of this value, 5 GW, as maximum charging power. This assumes that at any given time only 10% of vehicles stand still and are connected to a charging station. As can be seen in Figure 30, these 5 GW are fully used in summer during the day.

The next technology that can use PV overproduction is heat pumps and electric heaters (5). With the help of short-term thermal energy storage a heat pump can absorb PV generation during noon and deliver space heat and domestic hot water during the day. In addition, a seasonal thermal energy storage can shift heat from summer to winter and reduce the winter electricity demand (see also Figure 35). For process heat generation we see a seasonal pattern even without a seasonal storage: during the summer months heat is provided by electric heaters with short term thermal storage to deliver heat the whole day (see Figure 39). In the winter months when electricity is scarce a second system takes over, e.g. by burning wood or methane (fossil or biogenic). In this way, a scarce chemical energy carrier is used only when needed, namely in winter.

The last technology that can utilize summer PV generation is hydrogen electrolysis. It is very low in our base scenarios (see Figure 19) and does not appear in the case selected for Figure 30. Our sensitivity analysis indicates that electrolysis appears under conditions of higher import prices for methane and liquid fuels (see Figure 42 in Section 5.1). It is then used mostly for mobility purposes (see Figure 43).

The insufficient generation of photovoltaics in winter is the second issue to be solved. As shown in Figure 30, power generation by thermal plants and/or imports is present in the winter months for all scenarios. However, the production is always smaller for the innovative variant. The difference between a conservative and an innovative variant can be attributed to a number of factors: more hydro power and wind generation, increased reservoir storage volume, availability of alpine PV, more use of wood, better integration of bio-methane production with the gas grid, access to geothermal energy, seasonal thermal energy storage, etc. All of these factors impact winter electricity production, either by allowing more from non-thermal sources or by reducing demand for heat pumps and electric heaters.

These factors are controlled by Switzerland and can therefore be used to reduce winter electricity demand. The residual demand that is left even in the innovative variants amounts to 5-10% of the yearly consumption. It can be met by proper integration into the European energy system, most importantly the electricity system, but also by securing access to methane imports and by connecting to a possible future hydrogen network.

The next set of Figures shows the supply of space heat and domestic hot water for single and multi-family houses: Figure 31 and Figure 32 for ground-source and air-source heat pumps, respectively and Figure 33 for a wood pellet boiler. The latter is supported by solar thermal collectors that allow to save some wood in the summer months. These correspond to the archetypes listed in Table 1. In all cases a short term thermal energy storage allows to flexibly operate heat pumps or better integrate solar generation.

Figure 34 and Figure 35 shows the results for two types of district heating networks, namely a waste-to-energy plant and a large heat pump, respectively. The archetype of waste-to-energy plant follows the idea that was realized in Bern Forsthaus, namely to add a wood- and a gas-CHP plant. It serves in principle a residential district heating network and an industrial customer, however, we defined the first to be much larger, in line with the actual split of today. We consider also a seasonal thermal energy storage (S-TES, Innovative scenarios), a CO_2 separation from the combined flue gas of the three plants, and even a direct-air-capture unit that makes use of the fact that a CO_2 pipeline will be available.

Results show that the S-TES is used when available to shift heat from summer to winter. The importance of an S-TES is, however, reduced by the fact that the CO_2 separation requires heat throughout the year, creating effectively a baseload. In case of the Alone / Conservative scenario, a DAC unit is operated in the summer month to use the heat that would otherwise we wasted. Other factors that influence the relevance of an S-TES for a waste-to-energy plant are the amount of industrial heat that is supplied and the possibility to seasonally store waste (see Sections 0 and 6.4).

In case of a large heat pumps that serves a residential district heating network, the value of an S-TES is most obvious (see Figure 35). The heat pump can run at almost constant load throughout the year, reducing therefore investment costs and the demand for electricity in winter. **A simple model like the present cannot consider all possible technical issues of actually designing and operating such a system, this question must be addressed in WP3 of DeCarbCH.**

The next set of Figures shows the supply of medium temperature process heat. Three types of archetypes are selected by the model. When geothermal energy is available (Innovative scenarios) it is the preferred option. In the Conservative scenarios either a wood or a Gas-CHP unit with steam extraction is chosen, both supported by solar thermal collectors that save fuel in summer and by electrical heaters that deliver some peak demand in winter. **Whether or not geothermal energy can be made available in sufficient quantities is a key question and should become a priority in DeCarbCH (WP1). Also the integration of a CHP plant and solar thermal collectors with a short- to medium-term thermal storage should be studied in detail (WP4).**

A deficit of the present model is that industrial heat pumps that can be used to either improve the processes internally or to better match an external source as solar or geothermal to the process needs are not explicitly modelled. **This will have to be improved on close collaboration with WP5.**

The last type of demand is high temperature industrial process heat. Here, two archetypes from Table 1 are selected, a gas/liquid burner with additional electric heater and a solid wood/waste combustion for a cement plant. Figure 39 shows the interplay of burner and electrical heater. The latter is used in summer to harvest the PV peaks (supported by a short-term thermal energy storage) and for the Together/Conservative scenario also in winter to deliver peak demand. **This is a challenging arrangement that should be studied in WP4 of DeCarbCH.**

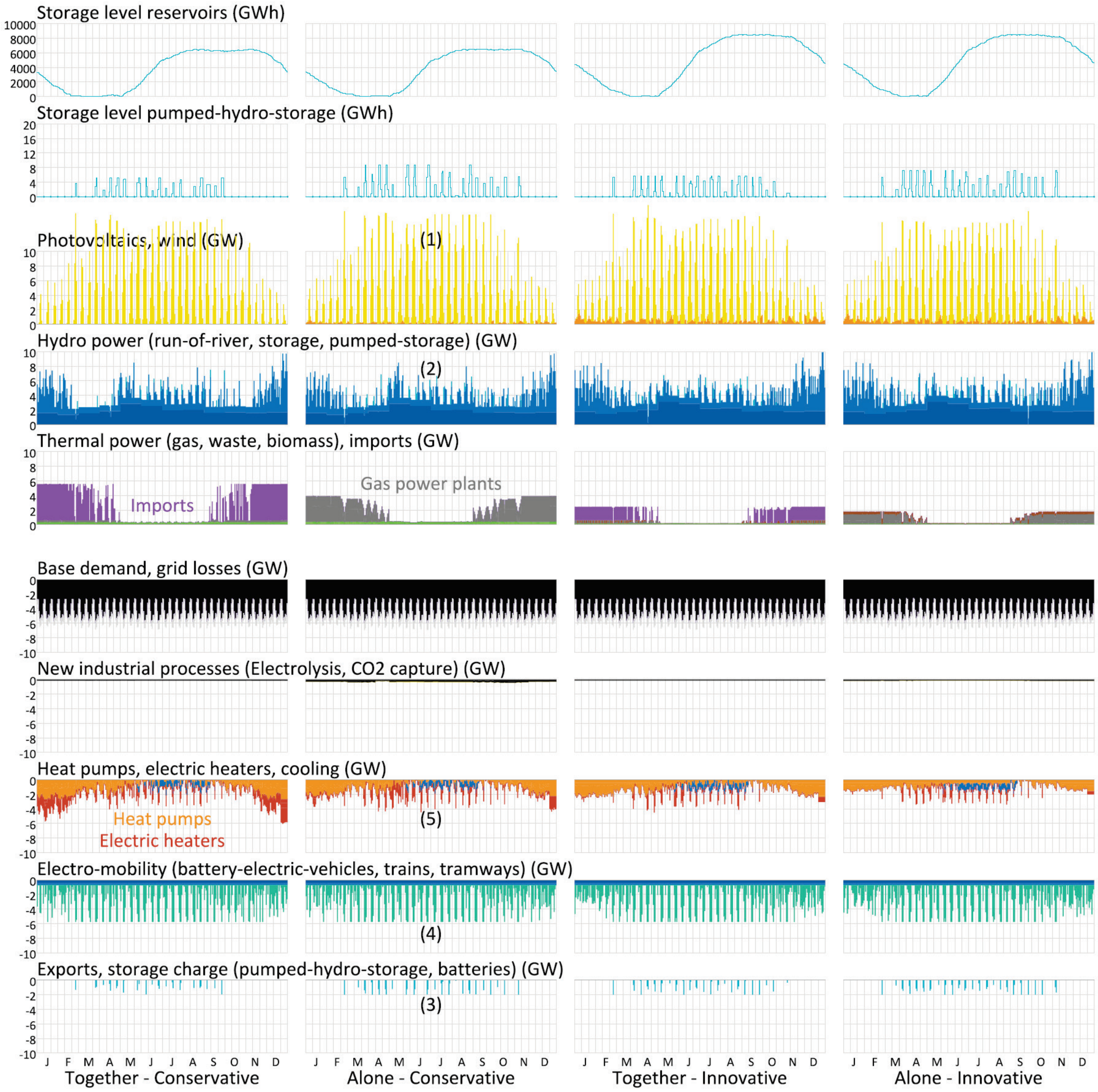

Figure 30: Electricity generation and consumption for the base scenarios at 6 Mt_{CO2}/a (Domestic).

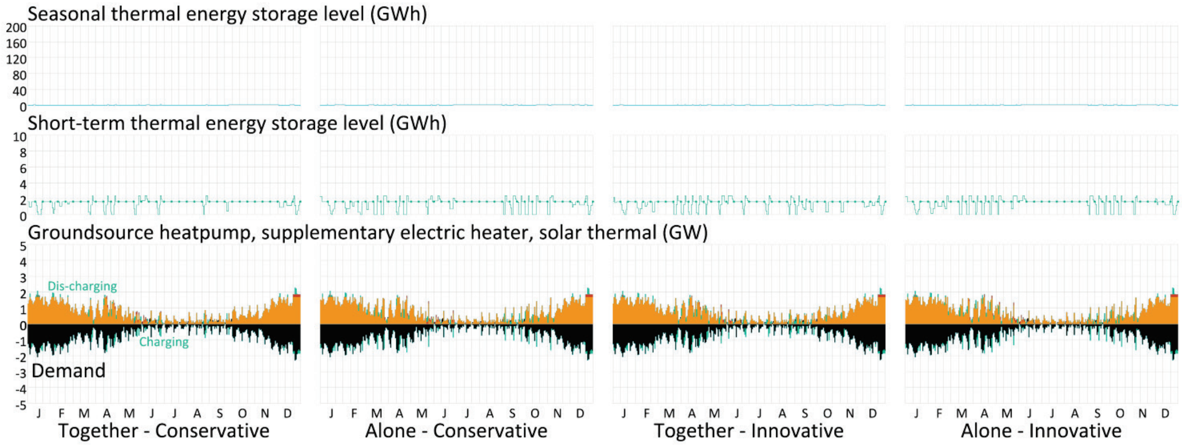

Figure 31: Ground-source heat pump in SFH/MFH for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype DEC1 in Table 1.

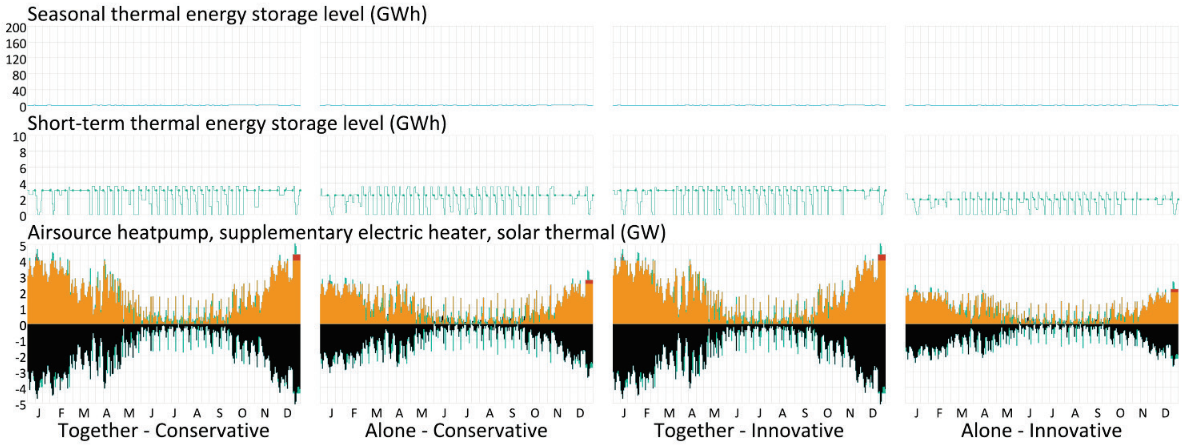

Figure 32: Air-source heat pump in SFH/MFH for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype DEC2 in Table 1.

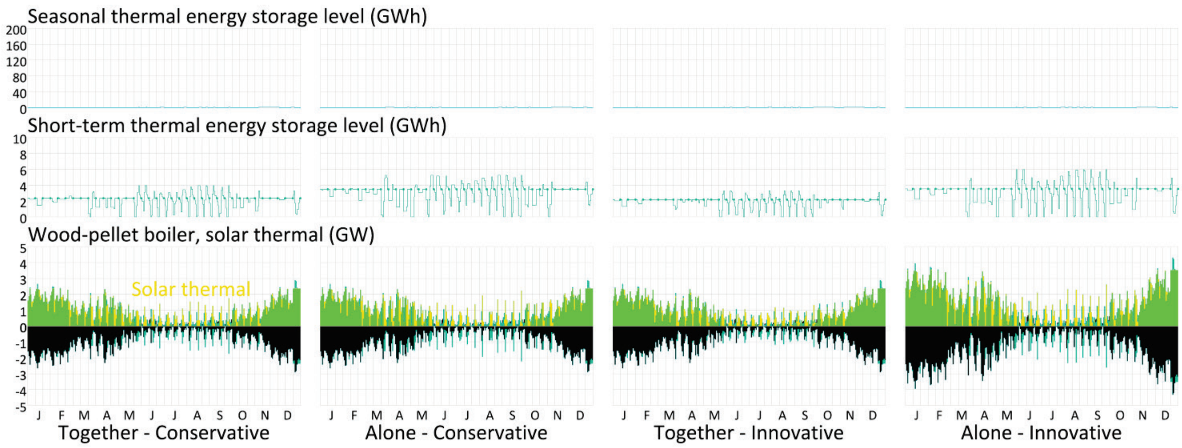

Figure 33: Wood pellet boiler in SFH/MFH for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype DEC6 in Table 1.

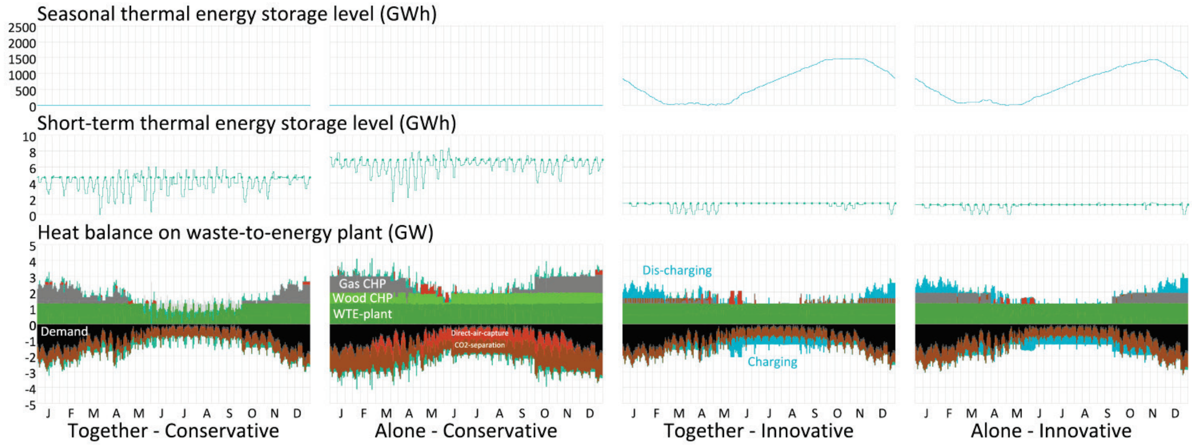

Figure 34: Waste-to-energy plant with wood- and gas-CHP, CO_2-separation and direct-air-capture for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype DHN1 in Table 1.

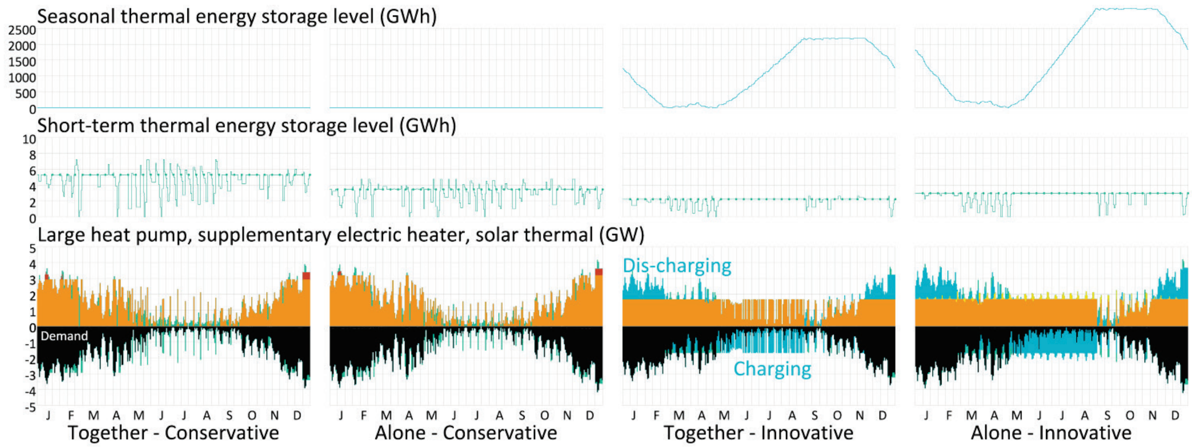

Figure 35: District heating network with large heat pump for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype DHN5 in Table 1.

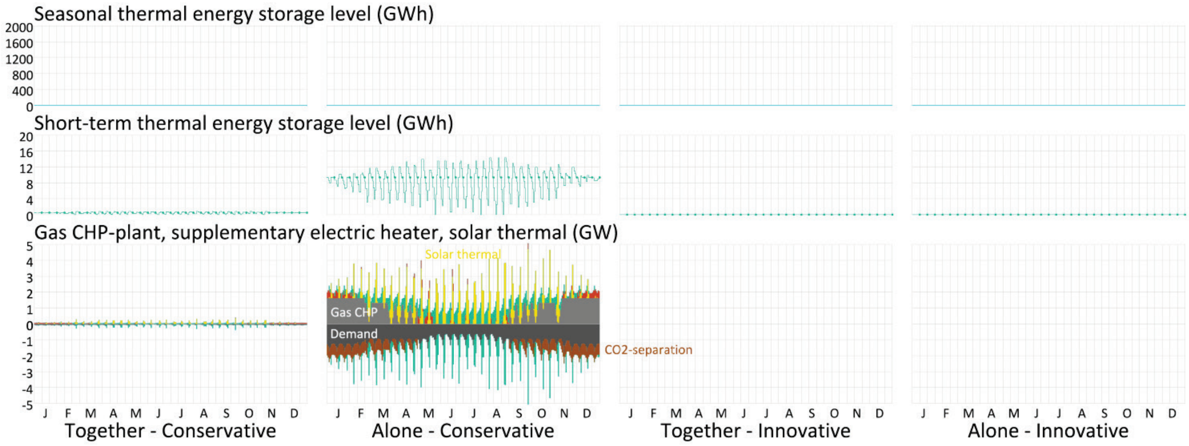

Figure 36: Medium temperature process heat by Gas-CHP plant for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype MTH1 in Table 1.

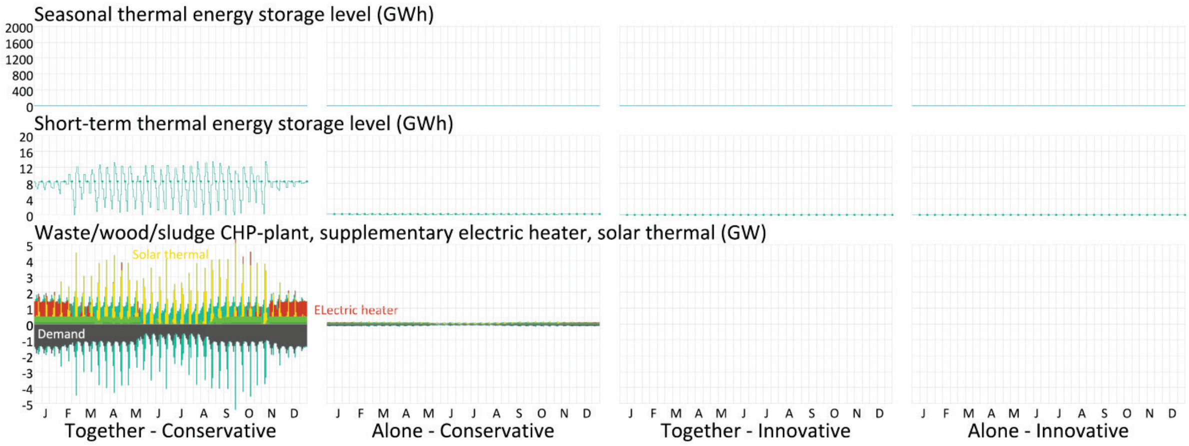

Figure 37: Medium temperature process heat by Wood-CHP plant for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype MTH2 in Table 1.

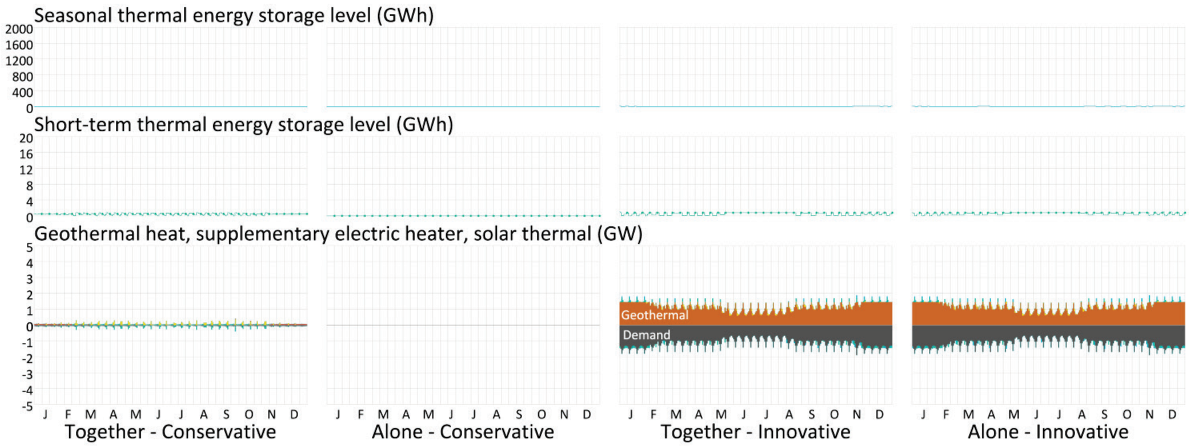

Figure 38: Medium temperature process heat by geothermal energy for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype MTH3 in Table 1.

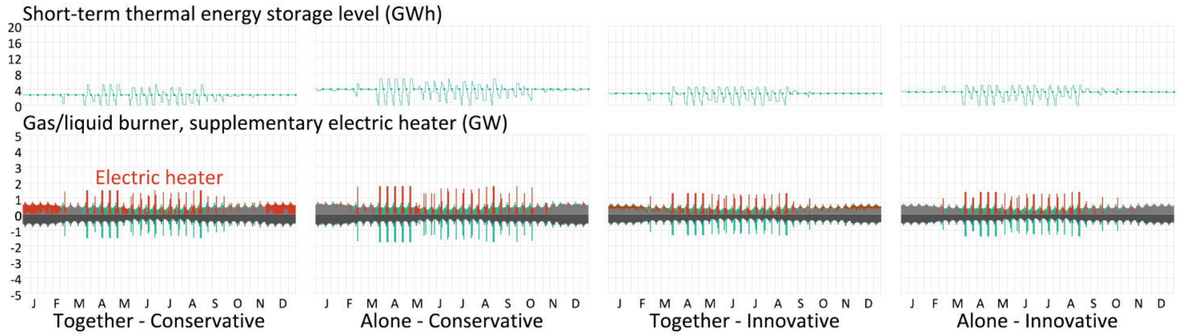

Figure 39: High temperature process heat by gas/liquid burner for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype HTH1 in Table 1.

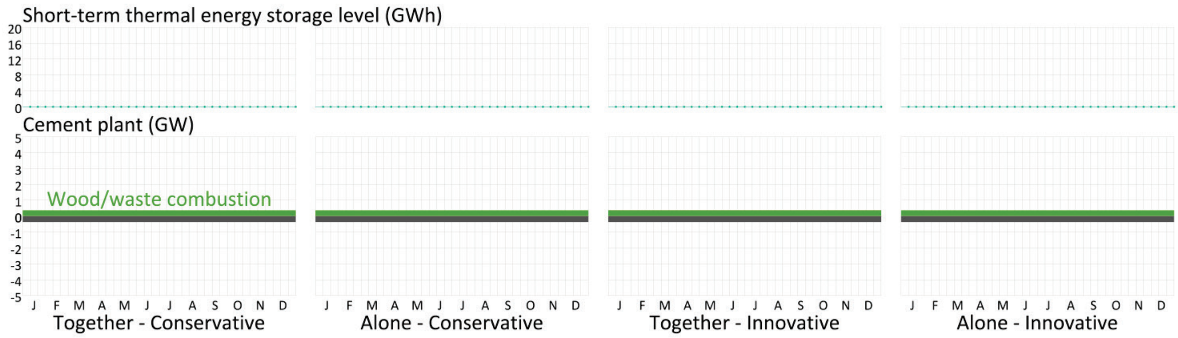

Figure 40: High temperature process heat by wood/waste burner in cement plant for the base scenarios at 6 Mt_{CO2}/a (Domestic); archetype MTH3 in Table 1.

4.8 Costs of reaching the net-zero target

As most bottom-up energy system models, SES-ETH performs a minimization of total system costs. This allows in principle to judge how much a net-zero energy system costs. However, this has to be interpreted with great care. Figure 41 (left) shows the marginal CO_2 avoidance costs, i.e. the cost to reduce emissions by one more t_{CO2}/a. This number increases for more ambitious CO_2 targets and reaches eventually 400 CHF/t_{CO2}. For CO_2 targets above 30 Mt/a, far above the net-zero targets defined in Section 3, this marginal avoidance cost goes down to zero. This can be interpreted as the optimal system configuration if CO_2 emissions have no price, i.e. the state where a business as usual scenario would settle.

We take this as a reference to compute the extra system costs that are needed to reach the net-zero target (right). The extra costs are the integral of the marginal costs (and the marginal costs the derivative of the extra costs). As explained in Section 3, the CO_2 target of +6 Mt/a (Domestic) represents the true net-zero to strive for. Figure 41 shows that the extra costs are in the order of 4-6 bCHF/a, roughly 0.5% of the GDP in 2050 or 400-600 CHF/a higher per capita costs. This is not a negligible quantity but surely far below anything that would cripple the Swiss economy.

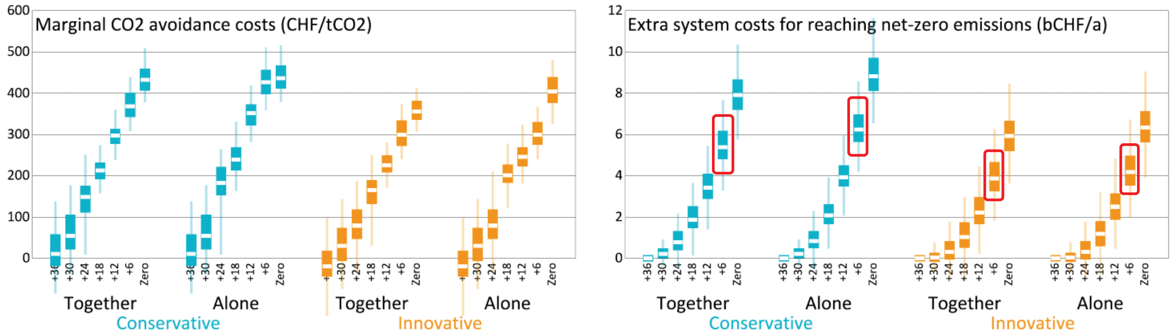

Figure 41: Marginal CO_2 avoidance costs and extra system costs to reach net-zero.

5 Sensitivities

The analysis of the base scenario in Section 4 provides important insights into the key elements of a future energy system. The stability of these insights is considered by having a total of 20 base scenarios. However, there may be other drivers or shocks that can in principle invalidate those insights. Some of these are studied in the present section. To assess the impact, a number of indicators have been selected that can be seen in the following Figures. The nomenclature and color coding is the same as in the previous section, but the figures show in addition the base scenarios in light grey.

5.1 Higher import prices for gas and oil

The first test is a tripling of import prices for methane and oil products, a scenario that is not unrealistic as the events in 2022 have shown (see Figure 44). The impact on the Together scenarios is small since we assume that electricity can still be imported in the same way. However, in the Alone scenarios the more expensive methane imports are compensated by a strong growth of photovoltaics, especially in the Conservative scenarios where methane imports are the highest. The reason is that hydrogen is not anymore produced by steam methane reforming but by electrolysis (see Figure 42). The overall production increases since some hydrogen is also used in CHP plants and industrial burners (see Figure 43). Since PV generation and electrolysis is concentrated in the summer months, some seasonal hydrogen storage is also required. Other indicators as the share of heat pumps or electric mobility or the amount of thermal energy storage are not affected by these higher import prices.

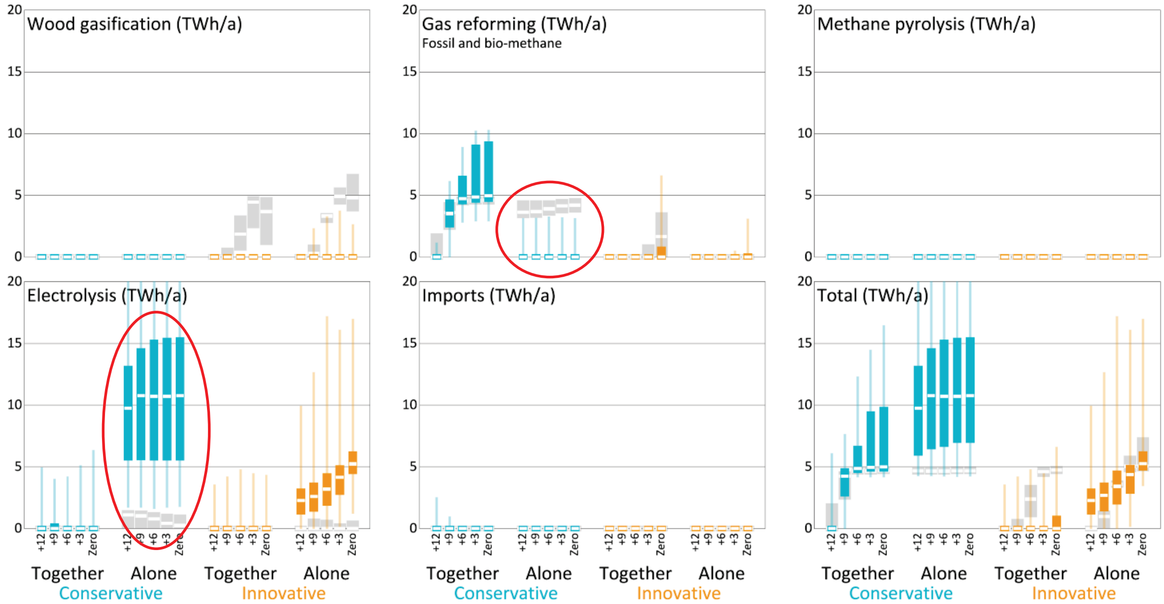

Figure 42: Hydrogen production routes; effect of tripling import prices for methane and liquid fuels.

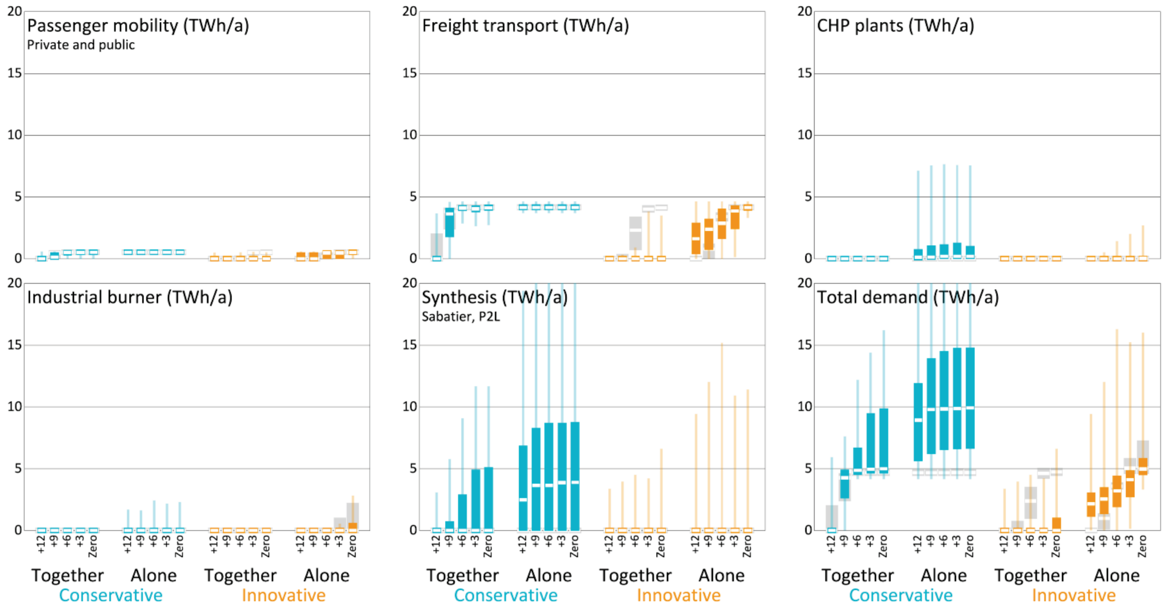

Figure 43: Hydrogen consumption; effect of tripling import prices for methane and liquid fuels.

Figure 44: Effect of tripling import prices for methane, diesel and kerosene.

5.2 Lower limit on maximum photovoltaic installation

Various estimates exist for the potential of photovoltaics in Switzerland. They generally agree that an installed capacity of 30-40 GW (corresponding to a generation of 30-40 TWh/a, see Figure 13) is feasible. We study the impact of a much lower upper limit to photovoltaic installations. This may be due to a lower adoption of rooftop PV or the unwillingness to accept large installations like agri-PV or alpine PV.

Results in Figure 47 show that a lower PV generation is compensated by either high methane imports (Alone) or by higher electricity imports (Together). In the first case, also the amount of stored CO_2 increases significantly. Since we assume that the necessary quantities of imported methane and electricity are available throughout the year, the need for seasonal storage of thermal energy, hydrogen and methane diminishes.

Having a lower PV generation changes also the cost structure for the overall energy system. As Figure 45 shows, the lower PV installation reduces investment costs but the higher need for methane or electricity imports dramatically increases operation costs leading to an overall higher total system cost. Figure 46 illustrates for the Alone scenarios the large share of gas turbine combined cycles throughout the year which is similar to today's role of nuclear power. The role of gas power is taken over by net imports for the Together scenarios.

Obviously, the situation can be interpreted from the other side: **installing a lot of PV reduces the necessity of electricity and/or methane imports, thereby increasing our resilience against shocks like the war in Ukraine.**

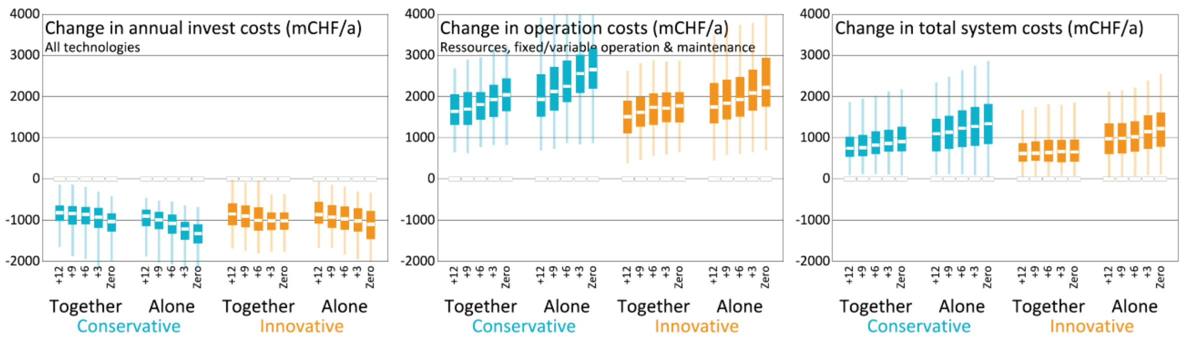

Figure 45: Effect of limiting installed PV capacity to 10 GW on investment, operation and total system costs.

Figure 46: Effect of limiting installed PV capacity to 10 GW; electricity generation and consumptions.

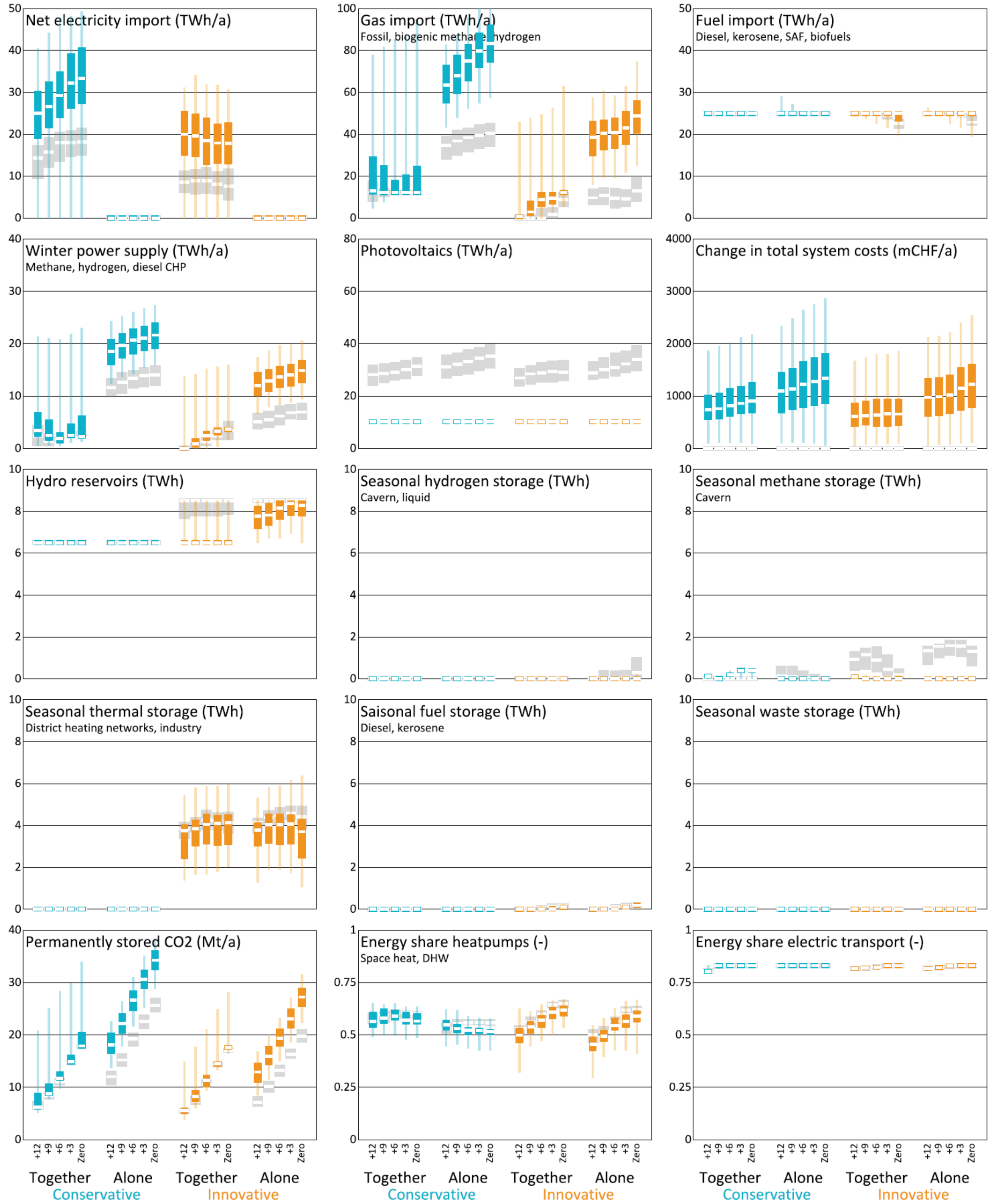

Figure 47: Effect of limiting installed PV capacity to 10 GW.

5.3 Lower availability of waste and wood

The potential for waste and wood has been estimated previously [4]. However, these extrapolations do not consider radical shifts that may reduce the energy potential significantly, e.g. a drive towards a circular economy that reduces waste volumes or a shift towards the use of wood in constructions that would lower the amount available for energy services. We can neither predict nor properly model these effects within the scope of SWEET-DeCarbCH, therefore the simple test is done to cut the potential of waste and wood by a factor of 2. Figure 50 shows that the lack of primary energy from waste and wood is compensated by slightly higher PV generation, methane and electricity imports. The reduced availability of wood for domestic heating increases the share of heat pumps. Annual system costs increase by up to 1 bio CHF. Figure 48 and Figure 49 show the effect on the consumption of waste and wood, respectively.

As for a lower limit on PV installations, the system reacts with higher imports to compensate the lack of primary energy input. **On the contrary, making this domestic resource available, reduces import dependency.**

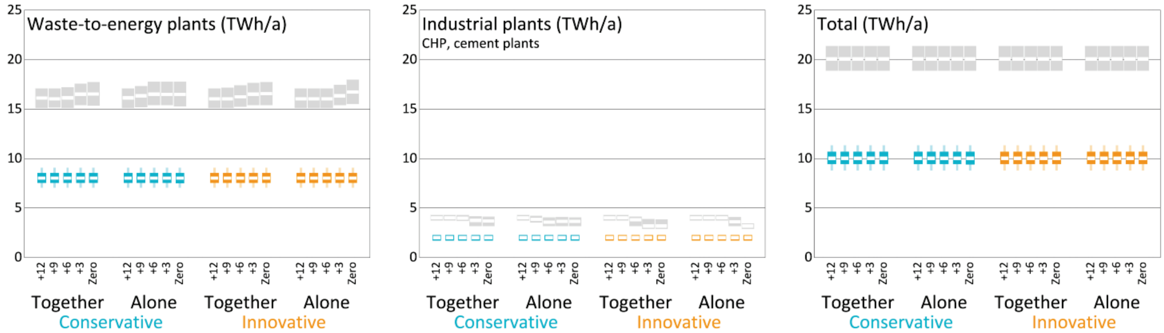

Figure 48: Effect of reducing available quantity of waste and wood by factor of 2 on waste consumption.

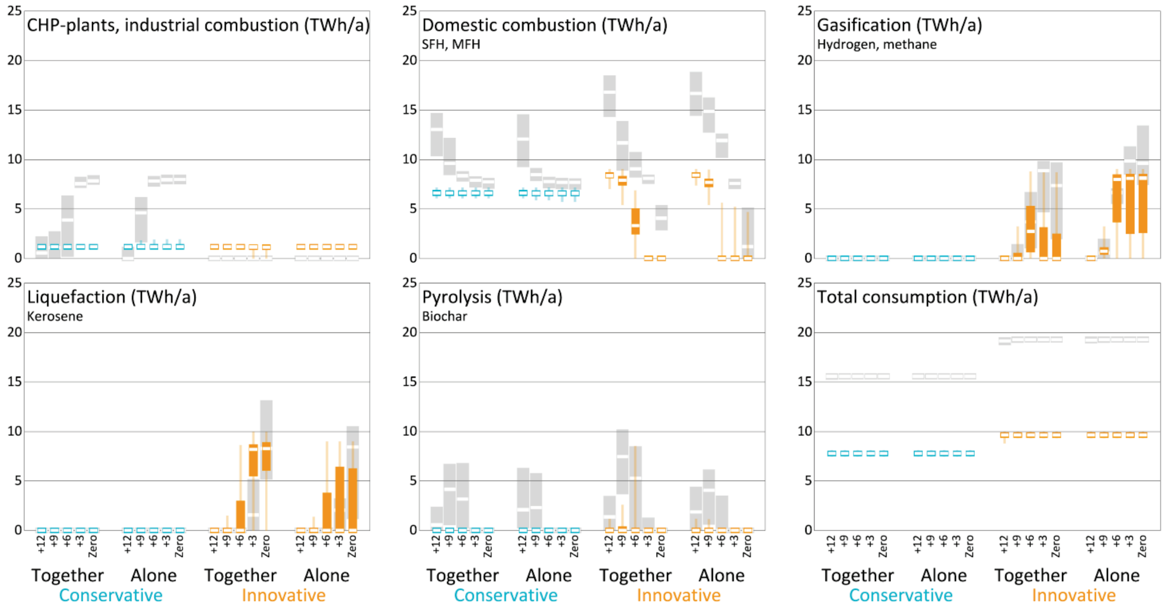

Figure 49: Effect of reducing available quantity of waste and wood by factor of 2 on wood consumption.

Figure 50: Effect of reducing available quantity of waste and wood by factor of 2.

5.4 Hydrogen imports

The Together base scenarios in Table 3 foresee an import of hydrogen at a certain volume and price which was defined in CROSS. The results show that this option is not chosen, the price of 160 CHF/MWh seems to be too high. A recent study by Empa assumed a much lower price of 75 CHF/MWh [12]. Figure 53 shows results for the usual indicators. Gas imports increase significantly, with a clear shift from methane to hydrogen (see also Figure 51). Electricity imports and PV production is reduced and compensated by hydrogen-based thermal power generation (see also Figure 52).

Independent of whether a hydrogen import price of 75 CHF/MWh is considered realistic, having the option to import hydrogen reduces the need for other energy imports and/or domestic PV production. Also the need for CO_2 storage decreases. **Switzerland should therefore be connected to a European hydrogen network.**

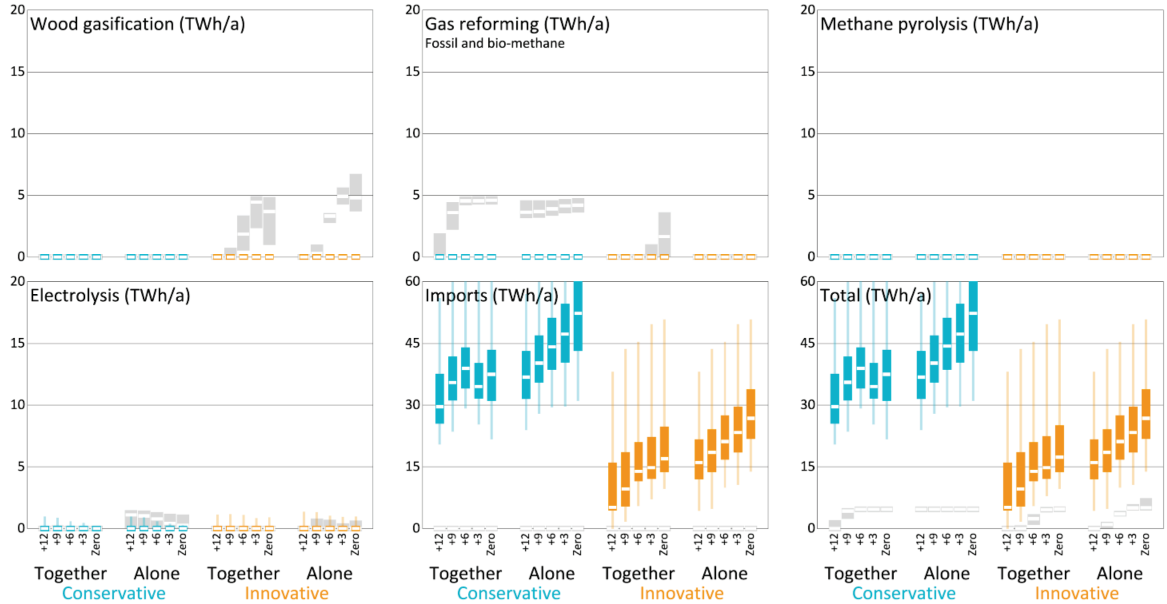

Figure 51: Effect of unlimited hydrogen imports at 75 CHF/MWh on hydrogen production.

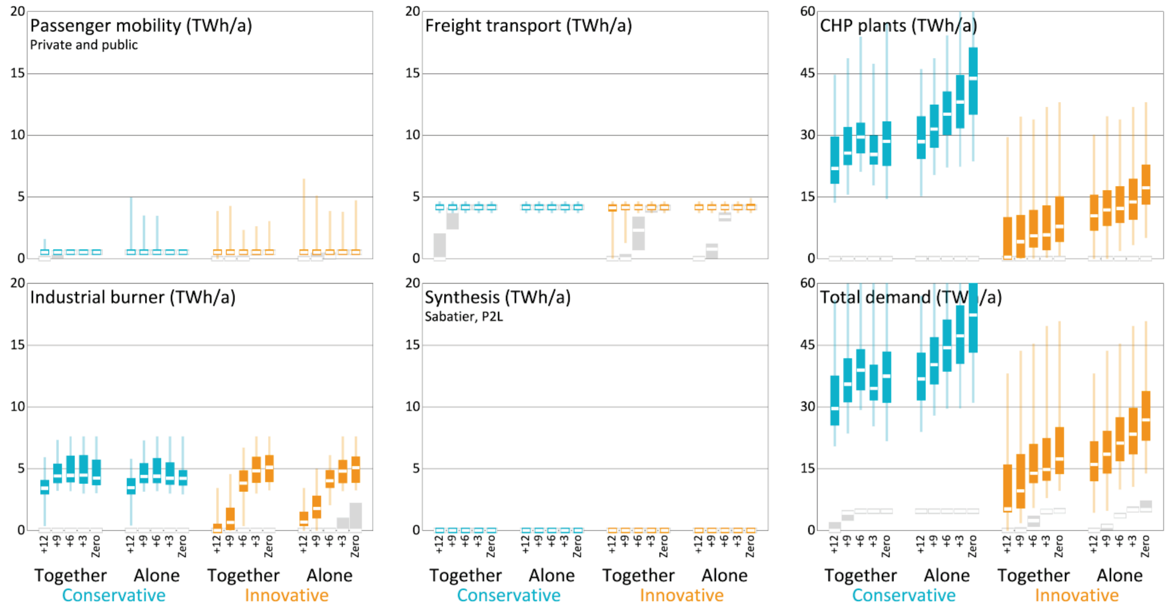

Figure 52: Effect of unlimited hydrogen imports at 75 CHF/MWh on hydrogen consumption.

Figure 53: Effect of unlimited hydrogen imports at 75 CHF/MWh.

5.5 Free relocation of WTE plants

At present there are 29 waste-to-energy (WTE) plants in Switzerland. Some are in the large cities (Bern, Zurich), others in rural areas (Linth), and a few deliver heat to an industrial customer (Lucerne) nearby. WTE plants are expensive assets that run preferably at design load. Furthermore, waste can generally not be stored (see also Section 6.4) and has to be burned continuously. As a consequence, the ideal location of a WTE-plant would be near to an industrial site where all the heat can be used directly.

In the base scenarios we enforce a certain share of heat delivered to residential district heating networks that mimics today's situation. In this section we consider the effect of releasing this constraint, creating a hypothetical situation that all WTE plants can be relocated as it is optimal for the energy system. Figure 55 shows the effect on the selected indicators. Interestingly, the influence on the Innovative scenarios is much lower than on the Conservative scenarios.

Figure 54 shows the annual time series for the heat balance on a WTE-plant, a gas-CHP plant and a geothermal plant. The first supplies a residential district heating system and some medium temperature process heat. The other two supply medium temperature process heat. In the Innovative scenarios, the S-TES solves the problem of mismatch between the constant heat supply of a WTE-plant and the seasonal heat demand of a residential district heating network, and the option to relocate the WTE-plant is not necessarily attractive. Furthermore, the Innovative scenarios have the option of geothermal energy that is used to supply low temperature process heat.

When neither an S-TES nor geothermal energy is available (Conservative), such a relocation is valuable because it allows to avoid the gas-CHP plant and its associated CO_2 emissions that would otherwise supply low temperature process heat. It is clear that such a relocation is mostly a thought experiment. **Nevertheless, WTE-plants have a limited life and some are planned to be rebuild within the coming years. The results suggest that a relocation to an industrial site should be considered if possible.**

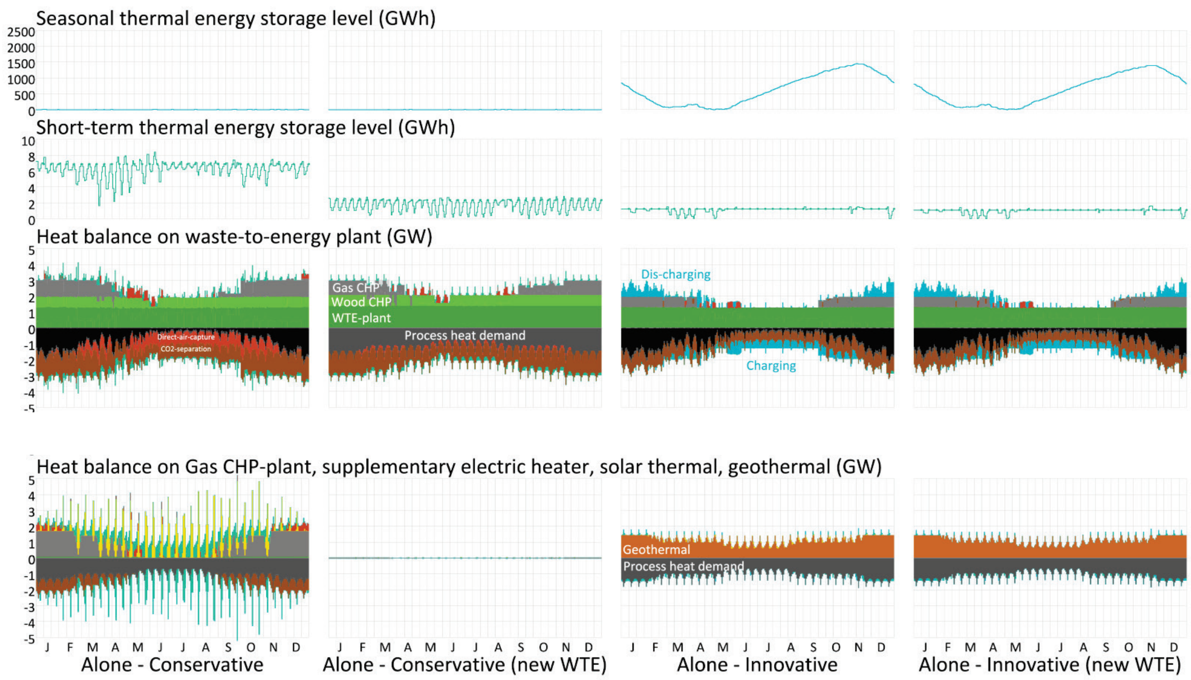

Figure 54: Effect of giving the option to relocate WTE plants.

Figure 55: Effect of free relocation of WTE plants.

6 Value of long-term energy storage

6.1 Seasonal thermal energy storage (S-TES)

Heat pumps are an essential element of a future net-zero energy system. They consume approx. 10 TWh of electricity, mostly in the winter months (see Figure 14). It is intuitively clear that a seasonal thermal energy storage (S-TES) that allows to run heat pumps in summer and store the heat for winter would be beneficial, given the fact that photovoltaic generation is abundant in summer and limited in winter. Other applications for an S-TES may be waste-to-energy plants that cannot utilize all heat during summer, or large scale solar thermal collectors for district heating networks or low-temperature industrial process heat. This section will quantify these benefits.

A recent overview study by FESS summarizes the options large scale S-TES [7] (see Figure 56). The most developed solution is the open pit storage, essentially a large excavation that is sealed to the ground with a plastic foil and covered by an isolation. A recent example is the storage in Vojens, DK with 200000 m3 (see Figure 57). The open pit has a depth of 13 m and covers an area of more than 15000 m2. This can be challenging in a densely populated country as Switzerland. Therefore, the alternative of underground thermal energy storage (UTES) is being researched in the HEATSTORE [8] project at locations in Geneva and Bern. We assume that such a technology will eventually be available at investment cost similar to a large open pit storage, namely 0.5-1.5 CHF/kWh.

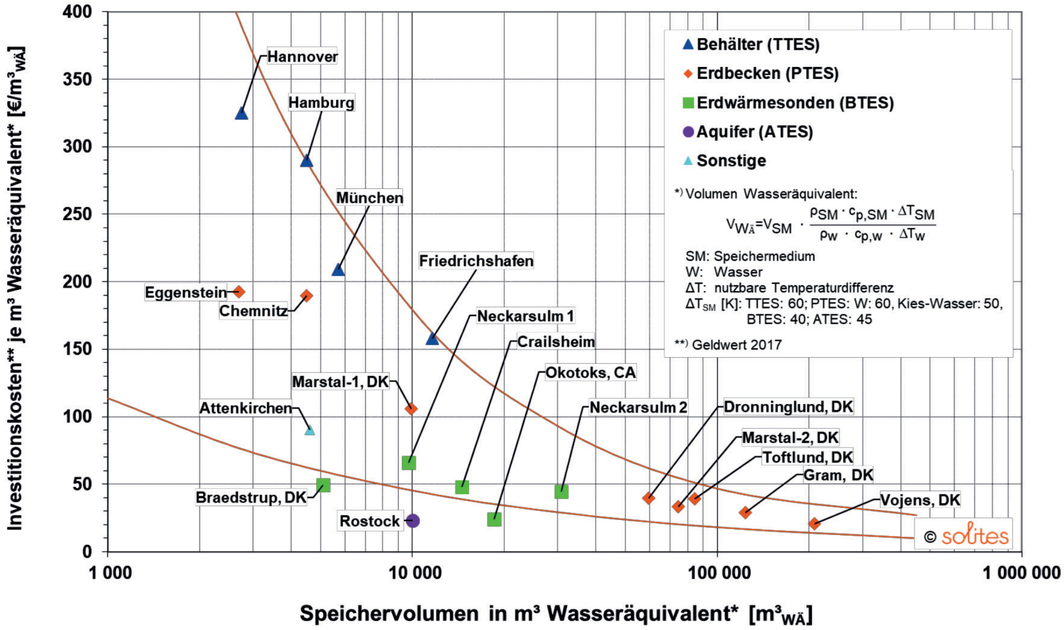

Figure 56: Investment costs for large thermal energy storage systems [7].

This section presents results that allow to quantify the value of having a seasonal thermal energy storage in Switzerland. As shown in Table 3, S-TES is an available option for the innovative scenario, but not for the conservative. However, comparing the two does not allow to isolate the effect of having or not having an S-TES. Therefore, two more variants are considered: an innovative scenario <u>without an S-TES</u> and a conservative scenario <u>with an S-TES</u>. These variants are analyzed again in the framework of CROSS scenarios, i.e. for a good (Together) and a poor (Alone) integration with the European energy markets, and for different ambitions of Swiss CO_2 targets (Compensation abroad – 12 Mt/a, Domestic – 6 Mt/a, True zero – 0 Mt/a).

Figure 57: 200000 m³ open pit thermal energy storage in Vojens, DK (see https://deepresource.wordpress.com/2020/12/16/district-heating-with-seasonal-storage-in-vojens-denmark/).

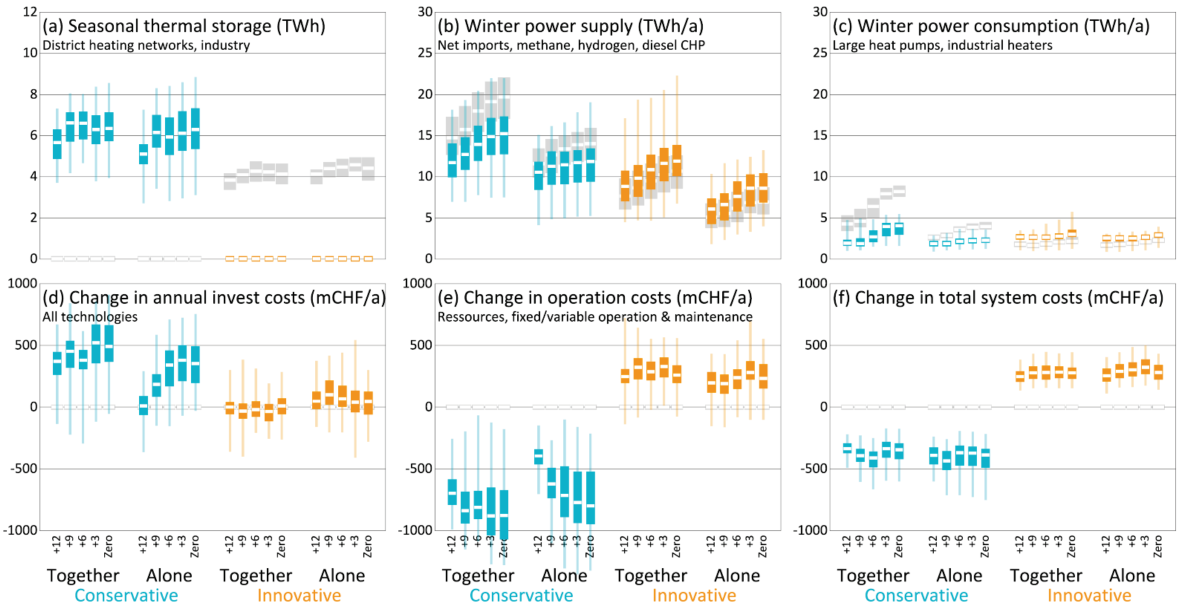

Figure 58: Effect of seasonal thermal energy storage.

Results are shown in Figure 58. Subfigure (a) reports the volume of S-TES. In the conservative scenario it is zero as defined in Table 3. When an S-TES becomes available for the conservative scenario, the volume increases to approx. 6 TWh. In the innovative scenario the volume if 4-5 TWh and it drops to zero if S-TES is removed. These numbers can be put in context with the hydro reservoir lakes in the Alps: these hold approx. 8.8 TWh of electricity (in the form of water). Subfigure (b) illustrates the effect on the winter power supply. This is defined as generation by gas turbines (methane, hydrogen, diesel) and/or net imports in the months October to March. Apparently, the winter supply decreases in the conservative scenarios when S-TES is added and it increases in the innovative scenarios if it is removed. Subfigure (c) shows that this is at least partly linked to a lower winter consumption by large heat pumps and industrial heaters. An additional indirect effect is related to photovoltaics: since summer production can be better integrated with the help of an S-TES, more photovoltaics is installed. This increases also the winter production, which in turn reduces the necessary production by thermal plants.

The low group of subfigures shows (d) annualized investment costs, (e) operation costs, and (f) total system costs, in each case as difference between the changed and the base scenario variant. For the conservative scenarios the investment costs increase, mostly due to the S-TES, itself. This is however, compensated by a decrease in operation costs, mainly due to a lower consumption of imported natural gas. As a consequence, the total system costs decrease by 400-500 mio CHF/a when a seasonal thermal energy storage is added in the conservative scenario. When S-TES is removed from an innovative scenario, investment costs change only slightly. However, an increase of operation costs – again due to higher natural gas consumption – leads to an overall increase of total system costs.

In summary, having a seasonal thermal energy storage available reduces the necessary winter electricity production by 2-3 TWh while saving costs in the order of several mio CHF. It also reduces electricity and natural gas imports, effectively reducing our import dependency (see Figure 59).

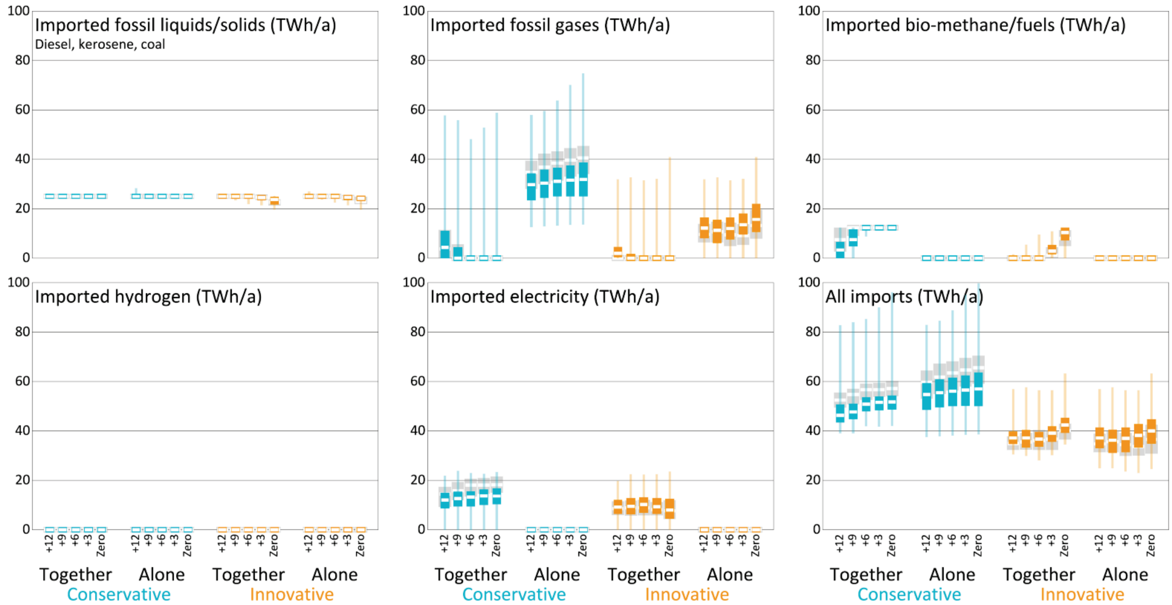

Figure 59: Effect of seasonal thermal energy storage.

Figure 60 shows the annual time series for electricity production and consumption for the Domestic scenarios at +6 Mt_{CO2}/a. It can be seen that indeed the production by thermal power plants (grey) decreases when switching from a no-STES to a with-S-TES scenario. As explained already, part of this reduction comes from the heating demand. In the no-S-TES cases, heat pumps operate at higher load in winter and close to zero in summer. When an S-TES is added, heat pumps (orange) operate also in summer and charge the storage. This heat is discharged in winter and reduces the electricity consumption. This effect can be seen even better in Figure 61 for the case of a large heat pump (orange) in a district heating network.

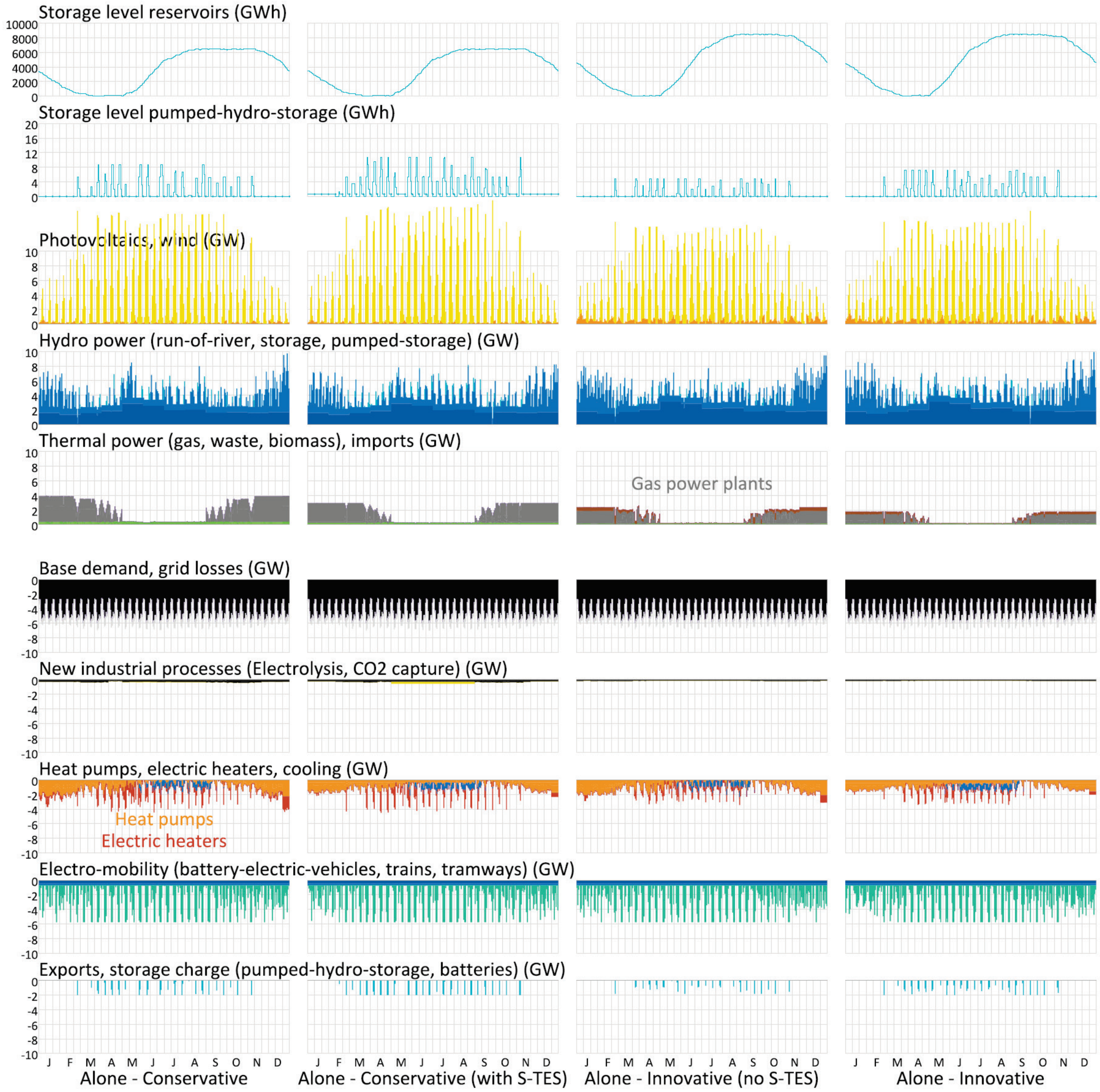

Figure 60: Annual time series for electricity production and consumption; Alone.

The effect on industrial process heat can be seen in Figure 62. Without an S-TES, the heat in winter is produced via a gas-fired CHP unit with steam extraction (grey) and additionally an electrical heater (red). In summer, the heat stems from a solar thermal collector field (yellow) with a short term thermal storage. When an S-TES is available, solar thermal energy can be charged in summer and made available throughout the year. This reduces both the need for an electrical heater and a gas-fired CHP plant in winter. In the innovative scenarios the heat is supplied by a geothermal energy system (dark orange).

The last application of an S-TES is in a waste-to-energy plant (see Figure 63). In absence of an S-TES the peak winter heat demand has to be covered by a gas-fired CHP plant, similar to the arrangement in Bern, Forsthaus. If an S-TES is available, it can be charged in summer by the surplus of heat from the waste incineration and it delivers the peak power in winter.

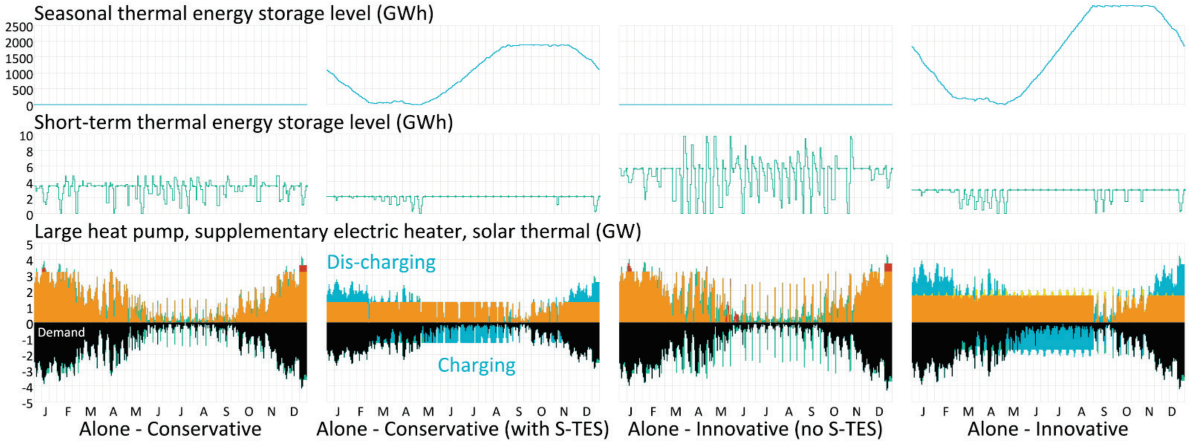

Figure 61: Annual time series for heat production and consumption in a district heating network with a large heat pump.

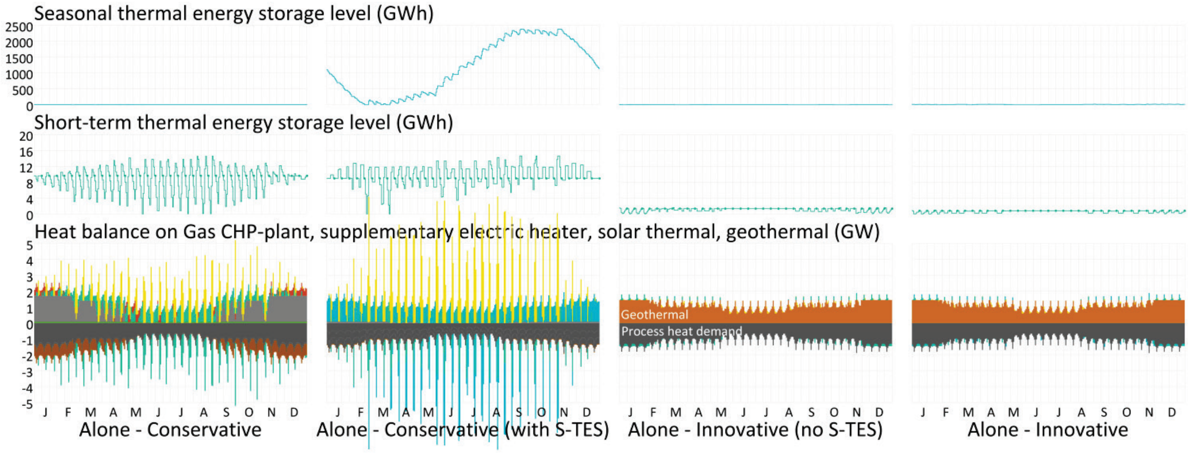

Figure 62: Annual time series for low temperature process heat production and consumption.

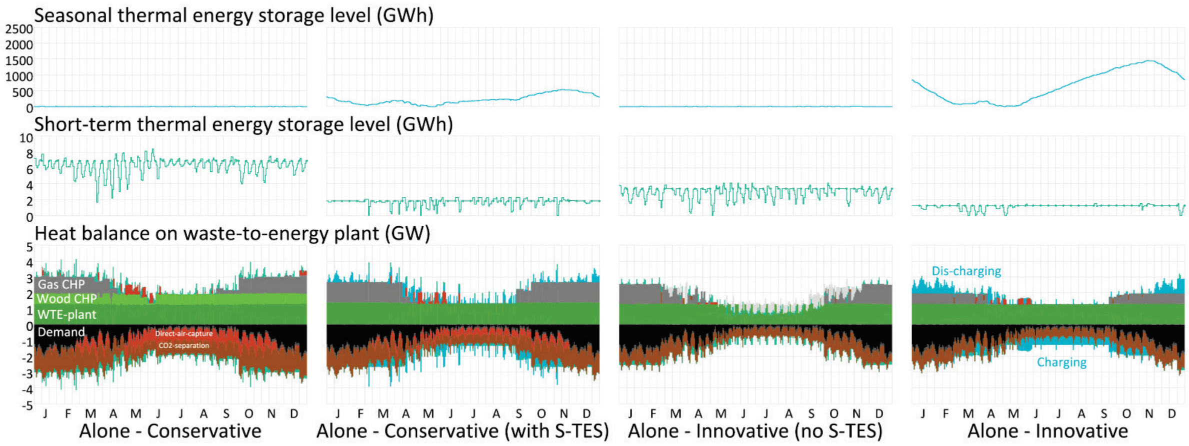

Figure 63: Annual time series for heat production and consumption at a waste-to-energy plant.

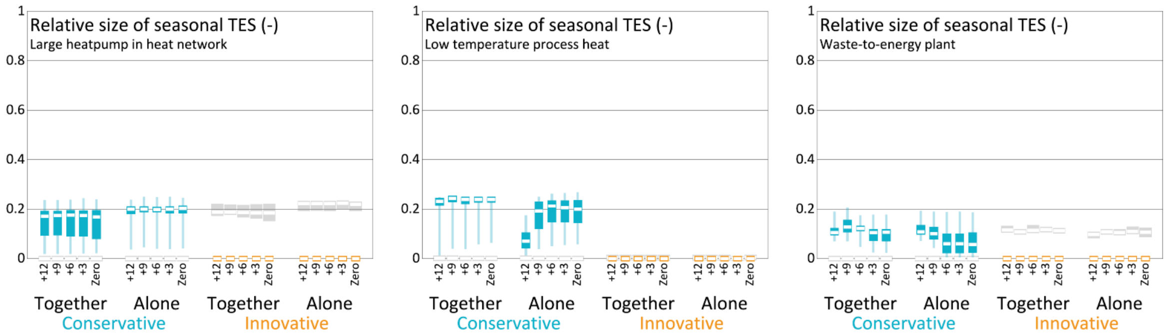

Figure 64: Size of thermal energy storage relative to the annual demand.

A last quantity of interest is the size of the seasonal thermal energy storage in relation to the total demand that is satisfied by the system. In the extreme case of an S-TES that is charged only during the summer months and discharged only in the winter month while covering the full demand, this ratio would be one. We consider again the cases of a large heat pump in a heat network, the low temperature process heat and the waste-to-energy plant. As Figure 64 shows, this ratio is actually in the order of 10-20%.

The following key learnings on the value of seasonal thermal energy storage can be summarized:

- A cost-optimal net-zero energy system should include a seasonal thermal energy storage (S-TES) with a volume of 4-6 TWh. Such S-TES may find application in:
  - District heating systems with large heat pumps. Here a smaller heat pump operates a larger number of full load and the peak demand in winter is covered from the S-TES.
  - Low-temperature process heat with solar thermal collectors. Here an S-TES can reduce or avoid the need for a secondary system (gas-CHP plant, electrical heater) that supplies the demand in the winter months.
  - Waste-to-energy plant. Here the S-TES allows to better utilize the heat that is generated in summer by the waste incineration, reducing again the need for additional gas power in winter.
- From an overall energy system perspective, the installation of an S-TES leads to higher investment costs. However, this is overcompensated by reduced operation costs, mainly for methane or electricity imports (and the costs for CO_2 separation, transport and storage). In total, having S-TES available reduces the annualized total system costs by 400-500 mio CHF.
- An additional effect of having an S-TES available is the reduction of winter electricity demand. This leads to a reduction of generation by gas-fired power plants and/or imports by 2-3 TWh. As a consequence, also the import of electricity and methane are reduced, decreasing our import dependency.
- Seasonal thermal energy storage is a proven technology that has found numerous applications in countries like Denmark. The main argument why the technology is not deployed in Switzerland is the lack of space for open pit storage. Another aspect is that the true monetary value of S-TES becomes apparent only for much lower CO_2 emissions than we have today in Switzerland. Nevertheless, we should not wait until we get closer to the net-zero target, the time to demonstrate the technology in Switzerland is now.

6.2 Alpine hydro reservoirs

The alpine reservoir lakes are filled mostly in summer by water from surrounding catchments. This water is made available to regulated hydro power plants (see Figure 65). Nominally, the volume of the reservoirs is 8.8 TWh, the amount of electricity that could be generated when all water is turbinated from a full to an empty status. In practice, the long term amplitude of reservoir level is rather some 6.5 TWh. The reservoirs are essential for the Swiss electricity supply as they supply both short term flexibility and the capability to store water from the summer months to the winter.

Hydro power was an important field of research in the SCCER-Supply of Electricity. A synthesis report highlighted key aspects of reservoirs, especially the opportunity to increase reservoir volumes by heightening the dams [9]. The equivalent increase in energy units could be more than 2 TWh (see Figure 66). The option to increase reservoir volumes from the aforementioned 6.5 TWh to 8.5 TWh is available for the Innovative scenarios (see Table 3). We isolate the effect of reservoir volumes on the usual indicators by performing the same experiment as in Section 6.1 for seasonal thermal energy storage (S-TES): the optimization are repeated for the Conservative scenarios with, and for the Innovative scenarios without an increase of reservoir volume.

The effect is comparable to the one for an S-TES: winter electricity supply by thermal plants, electricity imports or methane imports decrease approx. by 2-3 TWh/a for higher reservoir volumes. **Increasing reservoir volumes by dam heightening decreases therefore Switzerland's import dependency.**

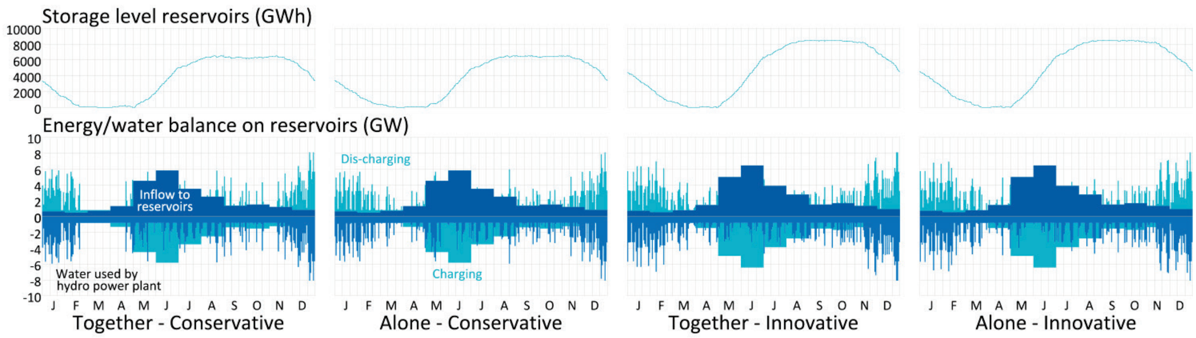

Figure 65: Operation of hydro reservoirs.

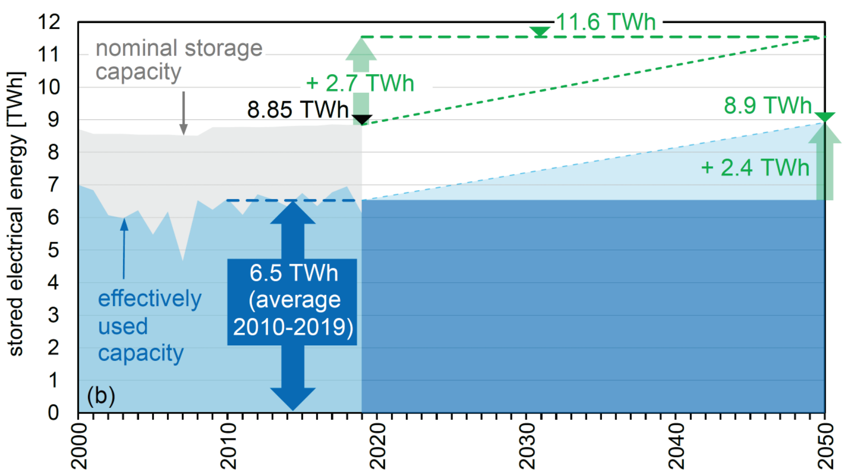

Figure 66: Possible increase of reservoir volumes [9].

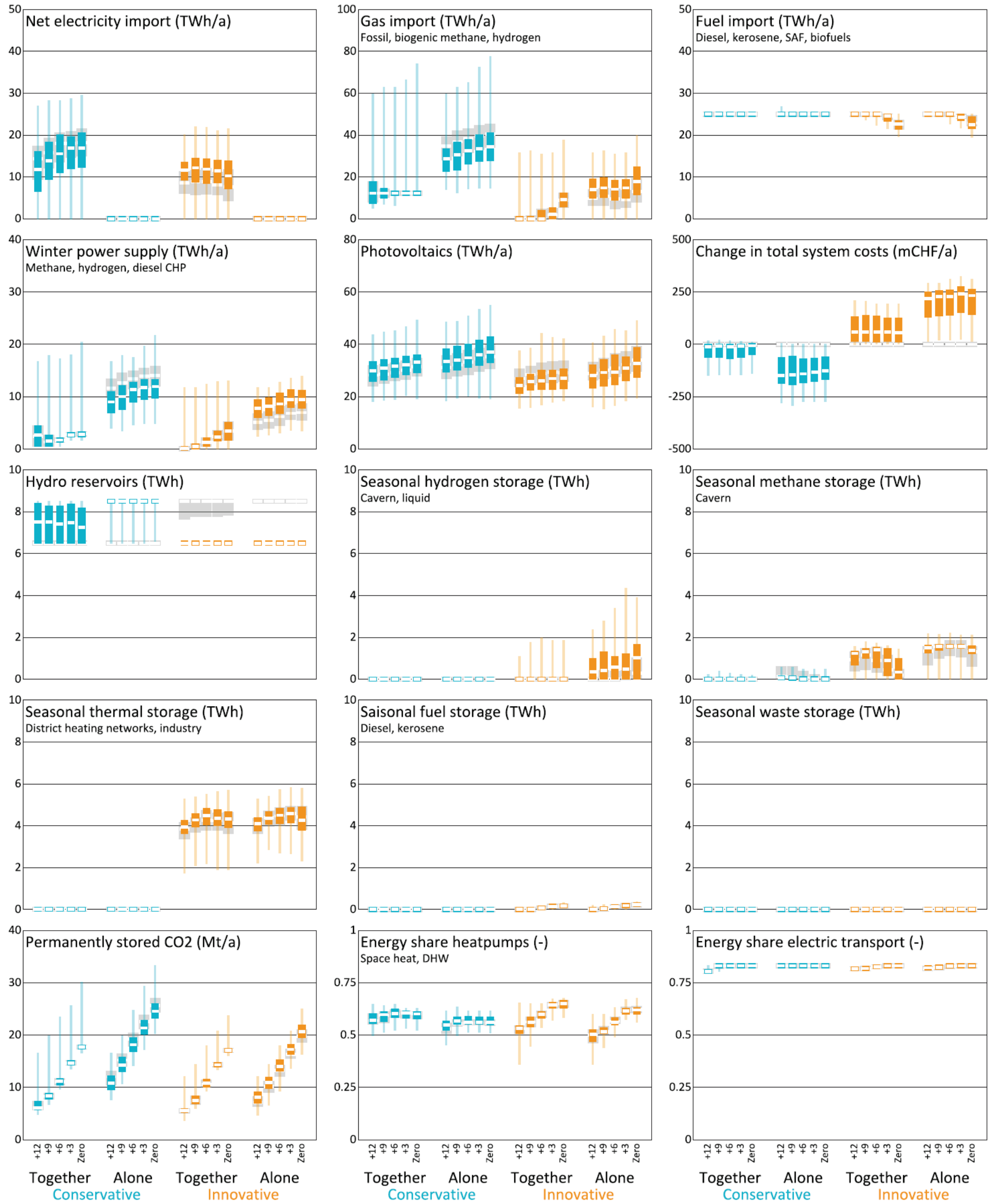

Figure 67: Effect of increased storage hydro power reservoirs.

6.3 Chemical storage (hydrogen, methane, liquid fuels)

Results so far show that a seasonal storage of chemical energy does not play a major role in future net zero scenarios. However, it is important to note here, that the SES-ETH model does neither consider dynamic import prices of chemical energy carriers nor the role of a strategic reserve. The optimal size of seasonal chemical storage may therefore be rather underestimated by this model. Some methane storage is used in the Innovative scenarios to shift bio-methane from summer to winter. It is almost absent in the Conservative scenarios since we assume no proper connection of rural biogas plants to a gas grid (see Table 3). When this option is taken away (see Figure 68), small adjustments can be seen, for instance a larger amount of methane imports and also a minor increase in total system costs.

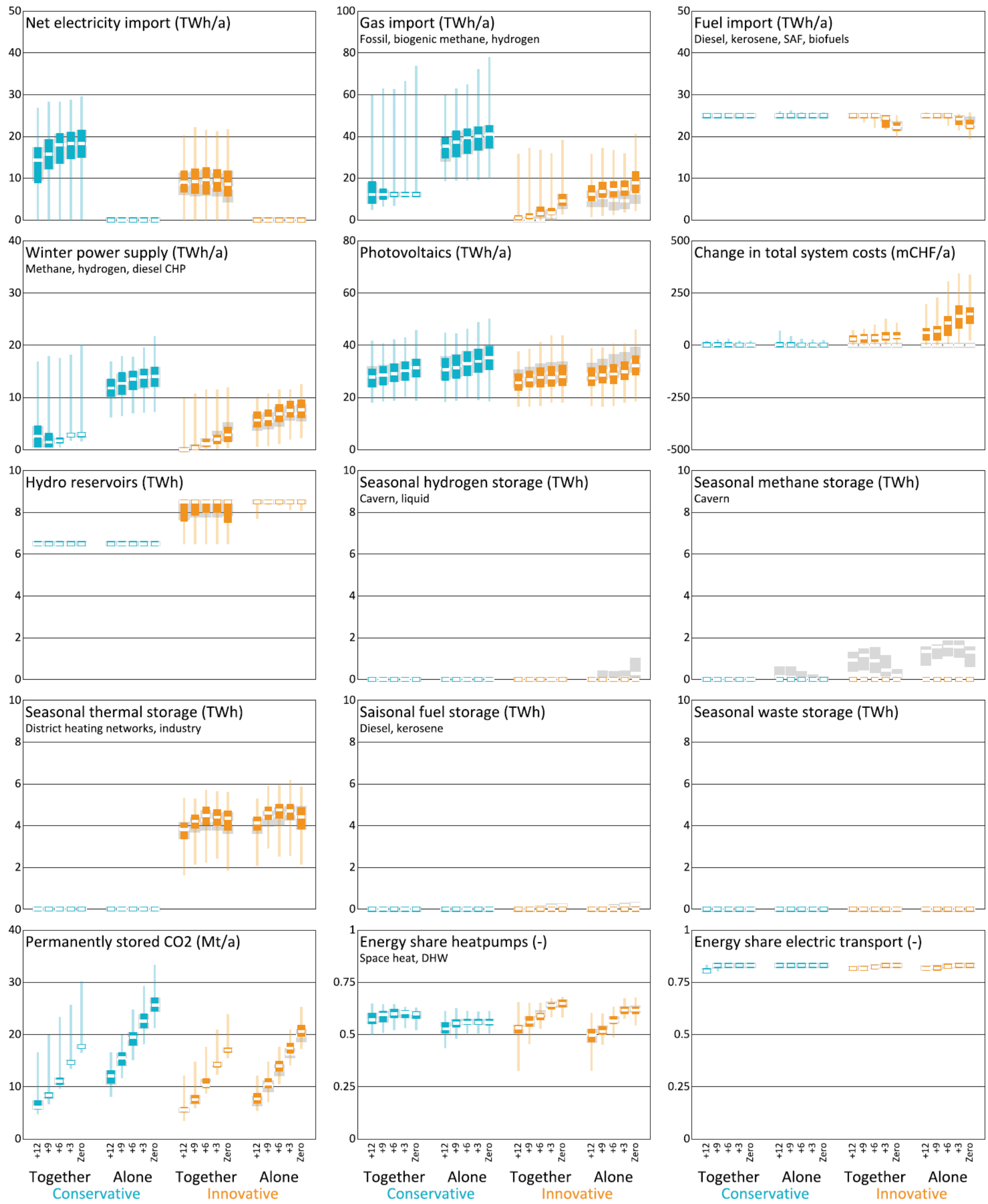

Figure 68: Effect of not having seasonal chemical energy storage.

6.4 Waste storage

Waste-to-energy plants serve multiple purposes, they dispose waste, deliver heat and electricity and in the future also negative emissions via CCS. As shown in Section 6.1, these plants can profit from a seasonal thermal energy storage (S-TES), that allows to store heat in summer that is not needed by a district heating network and use it to cover the peak demand in winter. An obvious alternative to this strategy would be to store the waste itself and use it when needed, i.e. mostly in the winter months.

Our results indicate that this value depends very much on the way the optimization problem is formulated. When the installed capacity of the waste-to-energy plant is a free parameter (as it is usually in the optimization), a waste storage is of little value. The explanation can be found with a thought experiment. Consider two cases of a district heating network that serve a residential area with a pronounced summer/winter demand pattern, one being fed by a large heat pump, the other by a waste-to-energy plant. The energy input – electricity for the heat pump and waste for the WTE-plant – shall be available without restrictions throughout the year. Both installations have high investment costs. Without an S-TES the heat pump has to follow the demand and be sized to the peak in winter. By investing into storage, the investment cost for the heat pump *decreases*, because it can now run at constant lower rate and matches the winter peak demand by discharging the storage.

The situation for the WTE plant is actually the opposite. Without a waste storage, the plant has to continuously consume the waste and run at constant rate throughout the year, rejecting some of the heat during the summer months when demand is low. When adding a waste storage, the heat rejection can be reduced and the heat is made available for winter but this requires an oversizing of the WTE-plant whose investment costs now *increase*. In summary, while for a heat pump the thermal storage reduces investment costs of the primary asset, in case of a WTE-plant investment costs have to increase in order to make the waste storage effective.

This changes when we reframe the optimization problem. Instead of giving the installed capacity free, we assume that there is a fixed capacity that is larger than the optimized capacity. This would be a case where some margin is available, as it is often the case in reality. This situation was modelled and the results are shown in Figure 70. There is a slight cost reduction for the Conservative scenarios and some minor reductions in gas and methane imports, but there is especially a reduction of installed seasonal energy storage capacity. This can also be seen also in Figure 69. **Since an S-TES will be challenging for many waste-to-energy plants, seasonal waste storage is an option to be explored.**

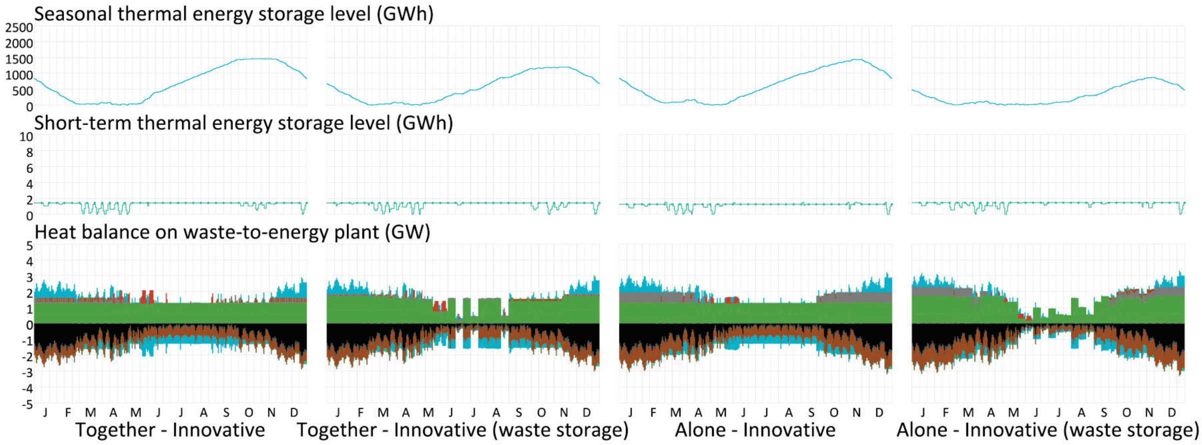

Figure 69: Effect of adding a waste storage for the Innovative scenarios.

Figure 70: Effect of adding a waste storage.

7 Value of negative emission technologies

Negative emission technologies (NETs) are capable of permanently removing CO_2 from the atmosphere. We consider here only technical means that are either based on the proper use of biomass or on direct air capture of CO_2 from the atmosphere. A clear definition of a NET is difficult and also of little use. A few examples may illustrate this.

- Direct Air Capture (DAC) with CO_2 storage is a NET. As such it may allow to compensate emissions from an aircraft that burns fossil kerosene. DAC may also be used to supply CO_2 for a fuel synthesis (using hydrogen from electrolysis) that allows to fly an aircraft CO_2-neutral. The effect for the climate is the same, but now DAC is not a NET.
- A gas turbine power plant that burns fossil methane and applies CCS is at best CO_2 neutral. The same plant becomes a NET when the fraction of bio-methane or SNG gradually increases.
- A hydrothermal liquefaction that produces diesel for freight mobility is not a NET. If the same Diesel is burned in a gas turbine with CCS it becomes a NET.
- A cement plant that burns coal and emits geogenic CO_2 from the calcination process may use CCS to become CO_2 neutral. When it switches from coal to biomass and applies CCS it can generate negative emissions. It would be absurd to apply CCS to the second and not to the first plant, only because the second generates negative emissions.

A further example may illustrate that the distinction between NET and pure compensation technologies is not helpful. Assume a cement plant and a wood CHP plant that both emit X kt_{CO2}/a. If the cement plant uses a fossil fuel its emissions will be positive, whereas they will be neutral for the wood plant. Now assume that CCS is applied to the cement plant. Overall emissions are now neutral, no CO_2 is added to the atmosphere. If CCS is applied to the wood plant, it generates negative emissions that compensate the emissions from the cement plant. Overall emissions are again neutral, although in one case a compensation measure was applied in the other a NET. The conclusion from these thought experiments is simple: after avoiding CO_2 wherever possible (by e-mobility, heat pumps, etc) it should be captured and stored / used whenever it is cost effective and it helps to reach our climate goal. NET are not "better" than compensation technologies such as CCS on a cement plant.

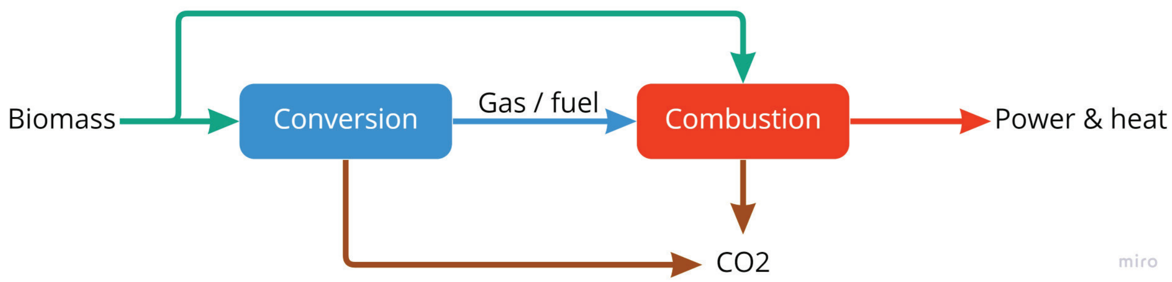

Figure 71: Two types of biomass conversion technologies.

Figure 74 shows a variety of technologies that allow to process various forms of biomass and that can be part of NETs. The technologies can roughly be grouped into two categories (see Figure 71):

- The first group encompasses technologies that convert one form of chemical energy carrier into another form. The starting point is often biomass, the product may be hydrogen, methane, a liquid fuel or carbon. In all but the last cases the process implies an increase of hydrogen and a reduction of oxygen content. Therefore, the process will usually lead to the formation of CO_2. This may be mixed with the product stream where it can/must be separated, or with air when it results from a combustion to provide heat to the process. If this CO_2 is separated and stored, the technology qualifies as a NET. Examples are anaerobic digestion, hydrothermal gasification/liquefaction and thermochemical gasification with subsequent processing to hydrogen, methane or fuels.

- The second group of technologies combusts a chemical energy carrier. This may be either in its raw form (wood, waste, etc) or the result of the aforementioned processing. The purpose will usually be the generation of heat and electricity. When CCS is applied to the flue gas, negative emissions can be generated. The precise quantification may however be difficult. Both synthetic and fossil methane will usually be mixed in a gas grid and the same may be true for liquid fuels such as diesel or kerosene.

A further difficulty is that any of the first technology category may not be a NET when CO_2 is not separated from the conversion step. However, the technology will become an NET enabler if the product is burned in a technology of the second category.

7.1 Technologies

A number of technologies are modelled in SES-ETH that are in principle capable to generate negative emissions, i.e. to extract CO_2 from the atmosphere. We group them as propose in the previous section.

Conversion technologies:

- Anaerobic digestion of green waste, manure and sewage sludge. All these technologies deliver biogas, a mixture of bio-methane and CO_2. In the technology innovative scenarios (see Section 3) we assume that such plants are connected to a gas and to a CO_2 grid, allowing for the biogenic CO_2 to result in negative emissions.
- Pyrolysis of wood. This thermo-chemical process results in biochar in which the carbon is chemically stable. When used for soil improvement it generates negative emissions. The drawback of this technology is the use of a scares resource like wood, that would deliver more energy and negative emissions when completely burned.
- Hydrothermal processing of digestate. The result of anaerobic digestion processes can contain still significant amounts of carbon that could not be digested by bacteria. In the technology innovative scenario we assume that this digestate can be collected and processed in a central facilities that operate hydrothermal gasification, liquefaction of carbonization.
- Gasification of wood. This technology converts in a first step wood into a syngas, i.e. a mixture of carbon monoxide, hydrogen, CO_2 and methane. In a subsequent step it may be further converted into hydrogen, synthetic methane or even liquid fuels (kerosene, Diesel) via a Fischer-Tropsch synthesis.
- Gas reforming of fossil or biogas. When operated with fossil gas, gas reforming cannot generate negative emissions, only low-emission “blue” hydrogen. When biogas is processed, also negative emissions are generated.
- Methane pyrolysis. This process spilt methane into hydrogen and carbon. When the latter is disposed, negative emissions are generated. The drawback over gas reforming is that some heating value is given up in the form of carbon. The advantage is that no gaseous CO_2 has t be stored.

Combustion technologies:

- Waste-to-energy plants. This includes the option to co-locate wood- and gas-CHP plants and to use a common CO_2-separation facility. Waste is considered 50% renewable in terms of carbon content. Examples for such a waste-to-energy hub is the plant in Bern Forsthaus.
- Industrial CHP plants that deliver electricity and process heat. These are equipped with CO_2-separation and can use gas, wood or waste as primary fuel. The amount of negative emissions depends on the fuel mix. An example is the plant in Domat/Ems.
- Wood CHP plants that deliver electricity and heat to district heating networks. These are equipped with CO_2-separation and use wood as primary energy, as a consequence they generate negative emissions. An example is the new plant in Galgenen.
- Cement plants emit CO_2 while generating the process heat and by the calcination process (CaCO3 → CaO + CO_2). When equipped with CCS they can generate negative emissions when biogenic fuel is used for the main process. In contrast to WTE plants, there is normally not enough low-temperature heat available for the CO_2-separation process. In this case, either an electricity driven pressure-swing absorption process is considered, or an additional wood-CHP plant that delivers the required heat.

Last but not least we consider direct air capture (DAC) of CO_2 as a negative emission technology. Many of the aforementioned technologies are also integrated with district heating networks. Whenever CO_2-separation is involved, a trade-off is made by the optimizer whether to use the heat for heating or for CO_2 capture.

7.2 Potential for CO_2 removal

We characterize the importance of a NET by considering two separate aspects: (1) the potential of removing CO_2 (Mt_{CO2}/a) and (2) the monetary benefit of having this technology available (bCHF/a, next Section 7.3). Figure 72 shows the amount of CO_2 that is captured from the various technologies (including the CO_2 equivalent of storing carbon). In order to better see how these quantities evolve with the CO_2 target, we repeated the analysis for 18, 24, 30 and 36 Mt/a.

The subfigure at the bottom shows the total amount of stored CO_2. It can be seen that CCS starts to become an option at a CO_2 target around 18 Mt/a. It is deployed at anaerobic digestion facilities (when available in the Innovative scenarios), and at large point sources such as cement plants, waste-to-energy plants or gas CHP plants. The marginal CO_2 avoidance costs at this CO_2 target is approx. 200 CHF/t_{CO2}. When approaching more ambitious CO_2 targets, thermochemical processes like gasification or gas reforming become a valuable option, now for CO_2 avoidance costs of approx. 300 CHF/t_{CO2}. The last technology to join the mix is direct air capture. It becomes relevant only from 6 Mt/a (Domestic) and grows strongly for the Real Zero scenario. Costs are then around 400 CHF/t_{CO2}.

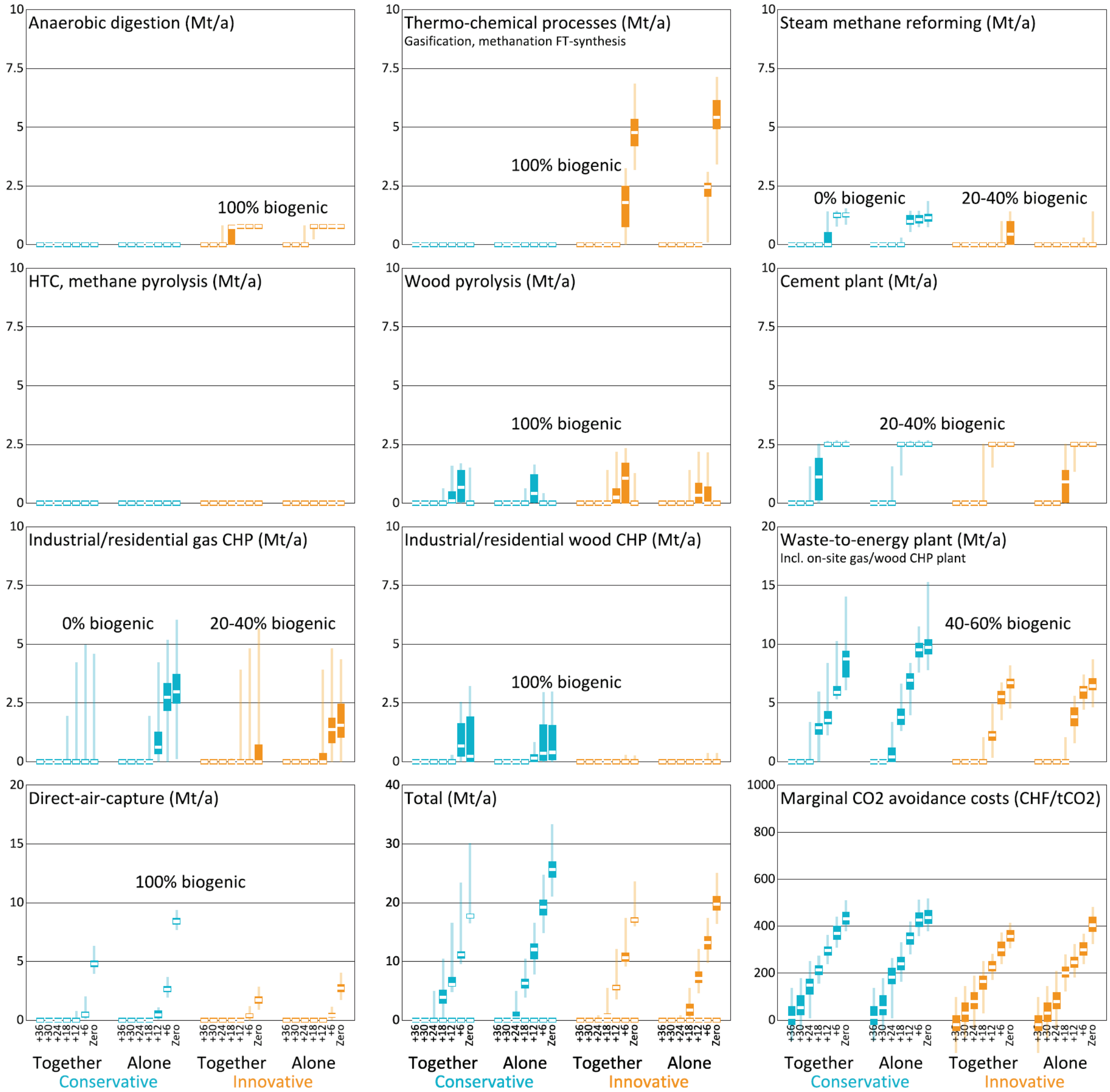

Figure 72: CO_2 capture potential of NET technologies.

7.3 Impact of not having a NET-element

Next we analyze the value of single NETs. Starting from the Alone / Innovative scenario we repeat the analysis by removing single elements of a NET. These are:

- Pyrolysis of wood to produce biochar
- Hydrothermal gasification/liquefaction/carbonization of digestate
- Rural clusters for anaerobic digestion of manure to bio-methane and CO_2
- Thermochemical gasification of wood to hydrogen, methane and liquid fuels
- Direct Air Capture
- CO_2 separation on gas CHP plants (outside waste-to-energy plants)
- CO_2 separation on cement plants
- CO_2 separation on waste-to-energy plants (with co-located gas/wood CHP plants)

The results of these experiments are shown in Figure 73, now again for the usual range of CO_2 targets from 12 to 0 Mt_{CO2}/a. Looking at the increase in costs shown in the first subfigure, it becomes clear that the most valuable technology is CO_2 separation from a waste-to-energy plant, together with anaerobic digestion and the HTX technologies, then comes CO_2 separation from cement plants. All other options are less essential when focusing on the 6 Mt_{CO2}/a target. This may seem a contradiction to the results shown in the previous Figure 72. For example, gas CHP plants with CCS exhibit a certain potential for CO_2 capture but only a low value for the overall system. This means that when CCS on gas plants is removed from the system, its role can be taken over by all the other options without a large cost burden. When removing CCS from waste-to-energy plants, the burden for the energy system is much larger. Direct air capture has a little value for the 6 Mt_{CO2}/a target but becomes indispensable when approaching the Zero target, in fact, there is no solution for Zero without DAC.

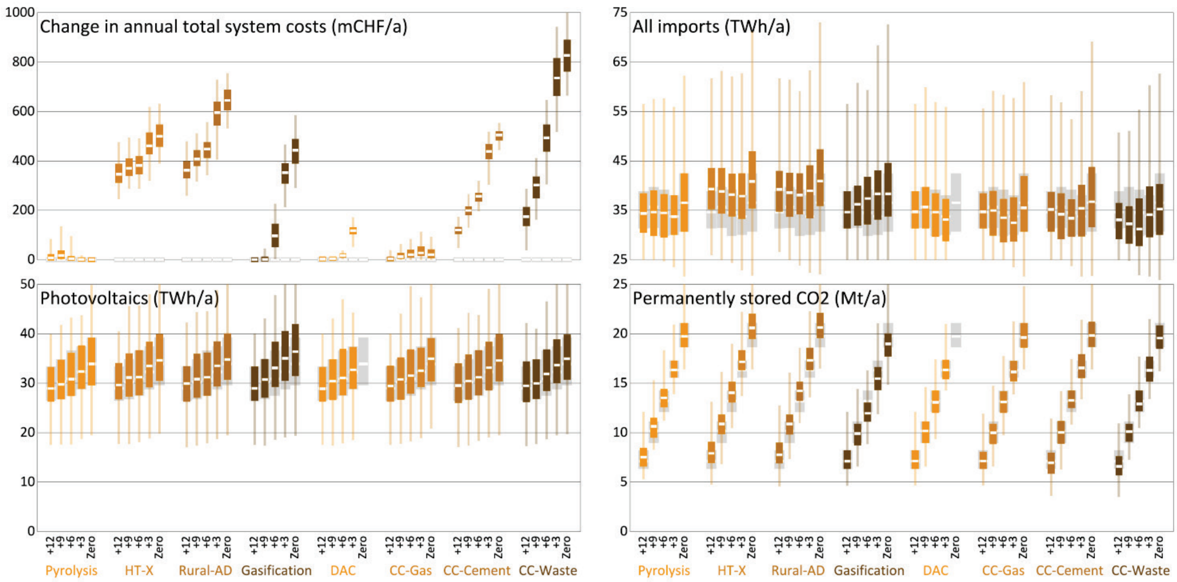

Figure 73: Impact of <u>not having</u> a certain NET-element.

The following priorities can be derived from this analysis:

- CO_2 separation and storage from waste-to-energy plants (possibly including onsite gas/wood CHP plants) should be the top priority. This option has both a large potential and a large value for the energy system. Other point sources such as cement plants or gas/wood CHP plants are technically similar.
- The proper treatment of rural biomass should receive more attention. A full industrial ecosystem can be established. This will include a centralized processing of residues such as manure in anaerobic digestion facilities, a proper biogas processing with a feed to the gas grid, a treatment of digestate in hydrothermal gasification/liquefaction or carbonization plants, a separation of CO_2 from the various processes with a connection to a CO_2 transport infrastructure (by truck, rail or pipeline). Last but not least, the proper management of nutrients as fertilizers must be considered.
- Biomass gasification is a valuable asset for the Zero scenarios but less relevant for the 6 Mt_{CO2}/a. The same is true for direct air capture. Both technologies may therefore be considered less relevant for Switzerland, however, at a global scale there is no doubt that these technologies will be essential, at least for producing sustainable aviation fuels.

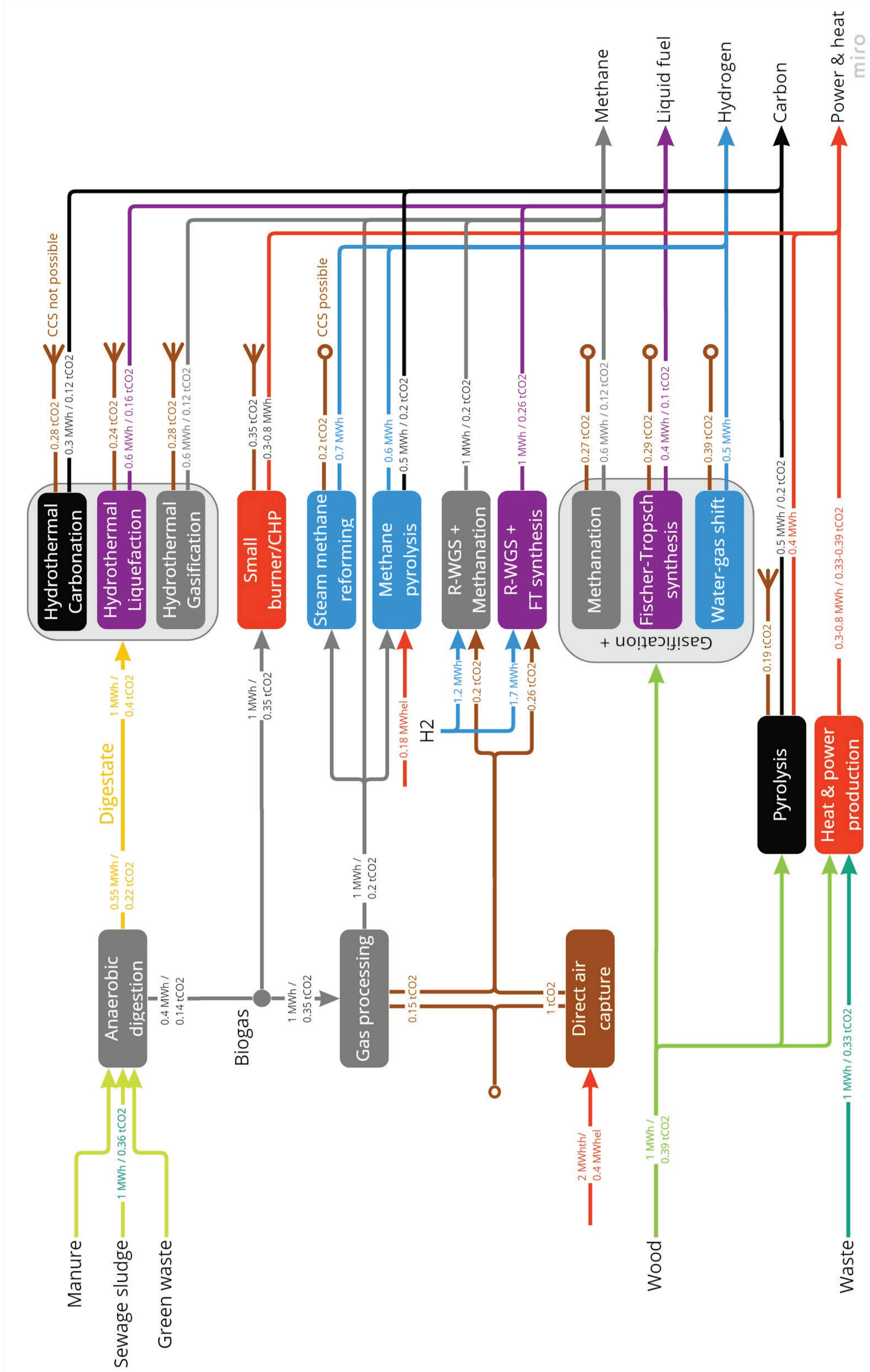

Figure 74: Connection of technologies that are capable of generating negative technologies.

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