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# SWEET Call 1-2021: DeCarbCH

# Deliverable report

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| **Deliverable No** | D1.4.2 |
| **Deliverable name** | Net-zero scenarios 2050<br>Focus topics: the value of innovative technologies |
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*“Good strategies for a radically uncertain world would acknowledge that we do not know what the future will hold. Such strategies identify reference narratives, visualize alternative future scenarios, and ensure that plans are robust and resilient to a range of plausible alternatives.”*

*“Rational people answer most questions about the future (…) by saying: I don’t know”.*

*John Kay, Mervyn King*
*Radical Uncertainty - Decision-making for an unknowable future*

# 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 practical implications. We use Swiss Energyscope (SES-ETH), an energy system model that was 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 in 2023 by implementing the CROSS scenarios (see Section 3). These have two main dimensions, the level of integration with the Swiss neighbors and the ambition in reducing Swiss $CO_2$ emissions domestically. We add a third dimension by defining a technology conservative and an 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 – sector coupling – 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 (20-40 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 5-15 TWh/a. Private battery electric vehicles will consume 14-16 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 thermal power plants that operate in the winter months and by electricity imports. Electrolysis – or power-to-gas – plays no role for seasonal balancing of the electricity system.
- Space heat and domestic hot water will be supplied to a large extent by heat pumps but also other sources such as combustion of waste, biomass or methane or solar and geothermal play an important role. Industrial process heat will be supplied by a mix of technologies, i.e. combustion of solid, liquid and gaseous fuels in CHP or combustion plants, direct electrical heating and geo- and solar-thermal for low temperature applications.
- Private vehicle mobility is largely electrified, some part of road transport requires a chemical energy carrier which could be hydrogen or synthetic liquid fuels.
- 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.

## 1.2 The value of innovation

Painting a picture of the future is enlightening but of little use without deriving practical actions for the present. We defined a number of innovative technologies and systematically determined the value that these technologies may have for the future net-zero energy system. This allows to set some priorities what needs to be done now.

- We considered various innovations in the heating domain such as low-temperature heat distribution systems, 5$^{th}$ generation district heating & cooling (5GDHC) networks or borehole regeneration. Using those technologies has the potential to reduce the necessary extra generation by thermal power plants and/or net imports by 3-5 TWh/a of electricity. This addresses directly the so-called “winter gap problem”. **In line with the general scope of DeCarbCH we therefore propose to prioritize further work on 5GDHC networks in WPX**.
- Whereas the first innovation addresses efficiency, geothermal energy is a new energy source to be exploited. Our results indicate that this new source would best be used for low temperature industrial processes, if needed with the help of an industrial heat pump. The use for residential heating suffers from lower operating hours whereas the use for power generation is not recommended due to the low electrical efficiency. The team will soon submit a proposal for additional funding that aims at **developing geothermal energy for such applications**.
- We also studied the proper use of wet biomass. Using the resource locally to generate biogas to produce heat and power is sub-optimal since the heat can generally not be properly utilized, electricity is produced also in summer when it has a low value and the opportunity to generate negative CO2 emissions is missed. An upgrading of biogas to bio-methane that is fed to the gas grid and CO2 that can be stored is essential. Digestate, i.e. the residues of the anaerobic digestion process, can be used as a solid fuel in industry or be converted to liquids and gases using hydrothermal technologies. **All these additions to the simple anaerobic digestion plant with a gas motor require quasi-industrial installations which can hardly be realized on the typical small Swiss farm. Therefore a centralization with a few dozens of facilities that are properly connected to the gas grid is highly beneficial**. In total, some 5-10 TWh/a of renewables fuels and gases could be produced by such installations. This subject is also central to the new SWEET refuel.ch project.
- The standard technology for CO2 separation is amine scrubbing. This is a complex process that may not be applicable for smaller size emitters such as industrial combustion systems or small wood plants in district heating networks. We studied membranes as a new option and indeed such a technology would be beneficial for the energy system as it would allow to capture CO2 from a larger number of point sources. **We recommend to prove CO2 separation by membranes as part of the P&D program**.
- Wood is one of the most valuable resources in the future. Its use has to be carefully optimized. Our results show clearly that while the use in pellet boiler for residential heat may be acceptable for high CO2 targets, a net zero energy system requires a more targeted use for higher value applications such as high temperature process heat or gasification/liquefaction to produce valuable energy carriers. It may seem a contradiction, but we also find the use of wood in the construction sector to be beneficial for reaching net-zero. Such approach constitutes a negative-emission technology since atmospheric CO2 is bound in the form of wood in a building. **Despite the needs of the energy system, wood constructions should be part of the negative emission technology mix.**
- In a close collaboration with SWEET-PATHFNDR we also studied value of flexibility in a future net-zero energy system. Besides the obvious flexibility providers such as batteries, pumped

hydro and storage hydro power stations**, especially the charging of electric vehicles is a game changing technology**. It allows to absorb a large part of the day/night fluctuations of photovoltaics. More detailed studies on this subject are underway in PATHFNDR and a collaboration will continue.

## 1.3 Variations to the base scenarios

As mentioned before, we base our conclusions on a large number of calculation where we vary assumptions on the integration of Switzerland with Europe, on our attitude to innovation and on further unknowns such as technology costs, import prices, etc. This increases the chances that our recommendations are valid and useful. Nevertheless, we considered further variations of the base scenarios and draw the following conclusions.

- The degree of autarky that we should strive for is a highly debated subject in the political arena. We consider this in the base scenarios with an Alone scenario that has no imports of electricity, hydrogen, biogas and biofuels, however, that allows still imports of fossil methane, Diesel and kerosene. In order to model a true “island scenario” we cut all imports except kerosene. The main changes we observe is a massive growth of photovoltaics (from roughly 30 TWh/a to more than 50 TWh/a) and hydrogen electrolysis – what is known as power-to-gas – that was not present in the base scenarios. Due to the low number of full load hours of photovoltaics, hydrogen production via electrolysis is expensive and the price for autarky would cost some extra 1000 mio CHF/a. **We conclude from this experiment that Switzerland should not strive for an island scenario but rather push its integration into the European power system.**
- An even more extreme reaction of the system can be observed when CO2 export and storage is removed as an option. The next best alternative is to use CO2 instead of storing it, namely to produce synthetic aviation fuels that avoid the import of fossil kerosene. However, this requires even higher amounts of photovoltaic generation and hydrogen electrolysis, and total system costs would increase by several 1000 mio CHF/a. Even then, the net-zero goal cannot be achieved. The insight we gain from this experiment is that CO2 use cannot replace CO2 storage and **that Switzerland must become part of a European CO2 transport and storage infrastructure.**
- The next experiment was to assume a low cost of hydrogen imports (2.5 CHF/kg) as proposed in last year’s VSE study. Under these conditions we observe a strong increase in hydrogen imports, reaching a similar level as today’s methane imports. This hydrogen is used for power and industrial process heat generation. Independent of whether such as low hydrogen price is considered realistic, it is clear **that Switzerland should be connected to a European hydrogen network**.

## 1.4 Outlook to next year

As mentioned before, the team plans to address the opportunities and challenges of 5GDHC networks in WPX and to propose the development of geothermal energy as a subject for an additional funding. 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 further improve the representation of industrial process heat and to implement the demand for platform chemicals that may be in competition with other uses of biomass.

# 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.

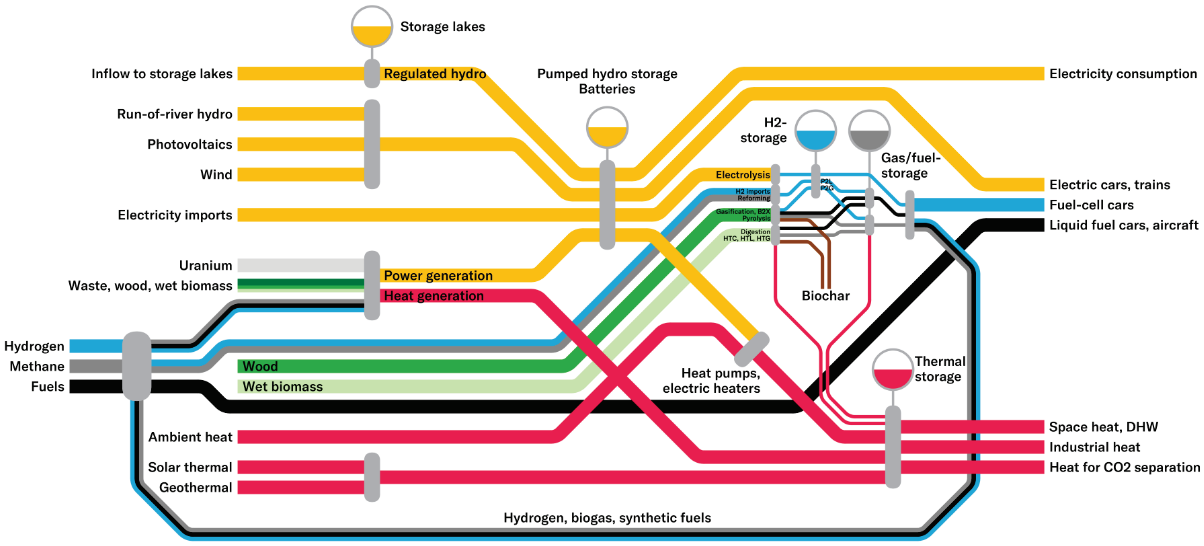


Figure 1: Schematic representation of the energy system as modelled in SES-ETH.

## 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

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

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

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

| | Gasoline | Wood | Electricity | Hydrogen | Gas boiler | Pellet boiler | Heatpump | DHN, wood CHP | DHN, geothermal |
|---|---|---|---|---|---|---|---|---|---|
| | Energy carriers (MWh) | | | | Space heat / DHW (MWh) | | | | |
| Ambient HEX | | | | | | | | | |
| Methane import | | | | | | | | | |
| Gasoline import | 1 | | | | | | | | |
| Wood supply | | 1 | | | | | | | |
| Electricity import | | | 1 | | | | | | |
| Hydrogen import | | | | 1 | | | | | |
| Hydro power | | | 1 | | | | | | |
| Photovoltaics | | | 1 | | | | | | |
| Wind | | | 1 | | | | | | |
| Gas turbine | | | 0.6 | | | | | | |
| Gas boiler | | | | | 0.9 | | | | |
| Pellet boiler | | -1 | | | | 0.8 | | | |
| Wood CHP | | -1 | 0.2 | | | | | 0.6 | |
| Geothermal | | | | | | | | | 1 |
| Heat pump | | | -1 | | | | 4 | | |
| Electrolysis | | | -1 | 0.6 | | | | | |
| ICV | -1 | | | | | | | | |
| BEV | | | -1 | | | | | | |
| FCEV | | | | -1 | | | | | |
| CO2 separation | | | -0.1 | | | | | | |
| Direct air capture | | | -0.4 | | | | | | |
| CO2 storage | | | | | | | | | |
| Batteries (charge) | | | -1 | | | | | | |
| Thermal storage (charge) | | | | | | | -1 | | |
| Hydrogen storage (charge) | | | | -1 | | | | | |
| Batteries (discharge) | | | 0.8 | | | | | | |
| Thermal storage (discharge) | | | | | | | 0.9 | | |
| Hydrogen storage (discharge) | | | | 0.9 | | | | | |
| Lights, motors, etc | | | -1 | | | | | | |
| Space heat, DHW | | | | | | | ∑ = -1 | | |
| Mobility | | | | | | | | | |

| | ICE | BEV | FCEV |
|---|---|---|---|
| | Mobility (pkm) | | |
| ICV | 0.3 | | |
| BEV | | 0.1 | |
| FCEV | | | 0.2 |
| Mobility (demand) | | ∑ = -1 | |

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

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

Demand rows: 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** | |
|---|---|---|---|
| DEC0 | – Ground-source heat pump with regeneration<br>– Electric heater<br>– Solar thermal<br>– Short-term TES | DHN1 | – Low temperature cooling & heating grid<br>– Water-source heat pump<br>– Electric heater<br>– Solar thermal<br>– Short-term TES<br>– Seasonal TES (optional) |
| DEC1 | – Ground-source heat pump<br>– Electric heater<br>– Solar thermal<br>– Short-term TES | DHN2 | – Mid-sized gas CHP plant<br>– Auxiliary gas boiler<br>– Solar thermal<br>– Short-term TES<br>– Seasonal TES (optional) |
| DEC2 | – Air-source heat pump<br>– Electric heater<br>– Solar thermal<br>– Short-term TES | DHN3 | – Wood CHP plant<br>– Solar thermal<br>– Short-term TES<br>– Seasonal TES (optional) |
| DEC3 | – Water-source heat pump<br>– Electric heater<br>– Short-term TES<br>– Long-term ice storage | DHN4 | – Small rural biogas plant<br>– Solar thermal<br>– Short-term TES<br>– Seasonal TES (optional) |
| DEC4 | – Gas boiler<br>– Solar thermal<br>– Short-term TES | DHN5 | – High temperature grid<br>– Water-source heat pump<br>– Electric heater<br>– Solar thermal<br>– Short-term TES<br>– Seasonal TES (optional) |
| DEC5 | – Oil boiler<br>– Solar thermal<br>– Short-term TES | DHN6 | – Deep geothermal source<br>– Solar thermal<br>– Short-term TES<br>– Seasonal TES (optional) |
| DEC6 | – Wood boiler<br>– Solar thermal<br>Short-term TES | DHN7 | – Small gas CHP plant<br>– Solar thermal<br>– Short-term TES<br>– Seasonal TES (optional) |
| | | DHN8 | – Pyrolysis plant<br>– Solar thermal<br>– Short-term TES<br>– Seasonal TES (optional) |
| | | DHN9 | – Waste-to-energy plant<br>– Wood CHP plant<br>– Gas CHP plant<br>– Auxiliary gas boiler<br>– Short-term TES<br>– Seasonal TES (optional) |

Table 2: Archetypes for industrial process heat.

| **Interm. temperature (<100 °C)** | | **Medium temperature (<200 °C)** | | **High temperature (>200 °C)** | |
|---|---|---|---|---|---|
| ITH1 | – Gas/oil CHP<br>– Electric heater<br>– Solar thermal<br>– Short-term TES<br>– S-TES (optional) | MTH1 | – Gas/oil CHP<br>– Electric heater<br>– Short-term TES | HTH0 | – Cement plant<br>– Wood/waste burner |
| ITH2 | – Wood/waste CHP<br>– Electric heater<br>– Solar thermal<br>– Short-term TES<br>– S-TES (optional) | MTH2 | – Wood/waste CHP<br>– Electric heater<br>– Short-term TES | HTH1 | – Gas/oil burner<br>– Electric heater<br>– Short-term TES |
| ITH3 | – Deep geothermal<br>– Electric heater<br>– Solar thermal<br>– Short-term TES<br>– S-TES (optional) | MTH3 | – Deep geothermal with heat pump<br>– Short-term TES | HTH2 | – Wood/waste burner<br>– Electric heater<br>– Short-term TES |
| | | MTH4 | – Solar thermal with heat pump<br>– Short-term TES<br>– S-TES (optional) | HTH4 | – Electric heater<br>– Short-term TES |

# 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 3 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.

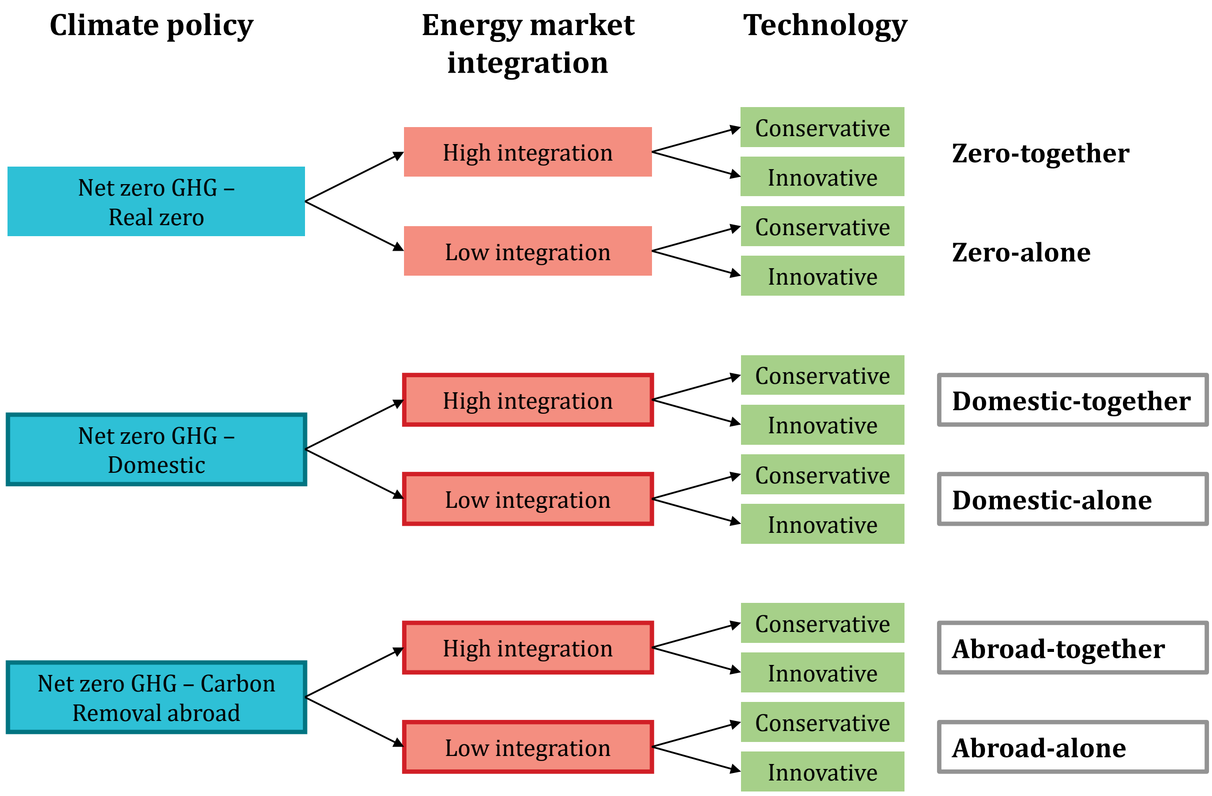


Figure 3: Basic scenarios for CROSS.

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 100-200 CHF/MWh | None |
| Methane imports | Unlimited at 30-60 CHF/MWh | |
| Kerosene imports | Unlimited at 50-100 CHF/MWh | |
| Diesel imports | Unlimited at 50-100 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 wet biomass anaerobic digestion | Yes | No |
| Hydrothermal conversion of digestate | Yes | No |
| CO2 separation by membranes | Yes | No |
| CO2 separation with integrated heat pumps | Yes | No |
| Conversion of waste/wood to gases/fuels | Yes | No |
| Low temperature convective space heat supply | Yes | No |
| Borehole regeneration | Yes | No |
| 5th generation cooling/heating networks | Yes | No |
| Negative emissions by using wood as building material | 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].

## 3.1 Improved model of heat pumps

It is widely accepted that heat pumps will deliver the largest share of space heat and domestic hot water in a net-zero future energy system. The electricity demand, however, depends on the source and sink temperatures, where the source may be the ambient air, the ground or a water body and the sink temperature is determined by the delivery system of the building. Last year's version of the SES-ETH model featured a very simplistic modelling of heat pumps assuming a COP of 3 for air-source heat pumps and a COP of 4 for all other types. In order to better assess the value of innovative technologies such as low-temperature convective heat delivery, borehole regeneration or 5[th] generation district heating and cooling (5GDHC) networks, a more sophisticated approach was needed.

The first step was to separate the demand for space heat, domestic hot water (DHW) and cooling. As mention in Section 2.2 the split for space heat into the various building archetypes is controlled by a variable that has to sum up to 1. We assign analogous variables to DHW and cooling with the extra constraint that the for each archetype the factor for space heat, DHW and cooling has to be identical. Then we defined the source temperature for 4 types of heat pumps, namely air-source, ground-source with and without regeneration and lake water (see Figure 4).

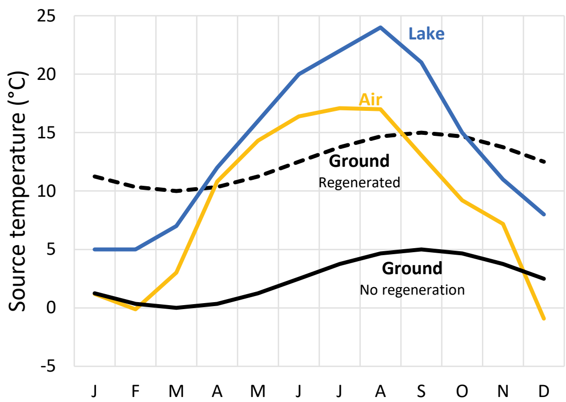


Figure 4: Source temperature for heat pumps.

The sink temperature is the temperature at which heat is delivered to a building. We assume that in a conservative scenario the sink temperature for space heat is 45 °C, for domestic hot water 50 °C. This corresponds to a situation with a underfloor heating or a radiator. In the innovative scenario we assume a switch to a convective heating that allows to reduce the sink temperature to 28 °C. We also assume that the temperature for DHW can be reduced to 40 °C. Given these sink temperatures and the source temperatures from Figure 4 we can pre-calculate a COP that varies with the months of the year (see Figure 5). For this we use the simple formula of a modified Carnot factor

$$COP = \eta_C \frac{T_{Sink}}{T_{Sink} - T_{Source}}$$

Where the exergetic efficiency (Gütegrad) is assumed to be 0.45 for air-source heat pumps and 0.55 for ground- or water-source heat pumps.

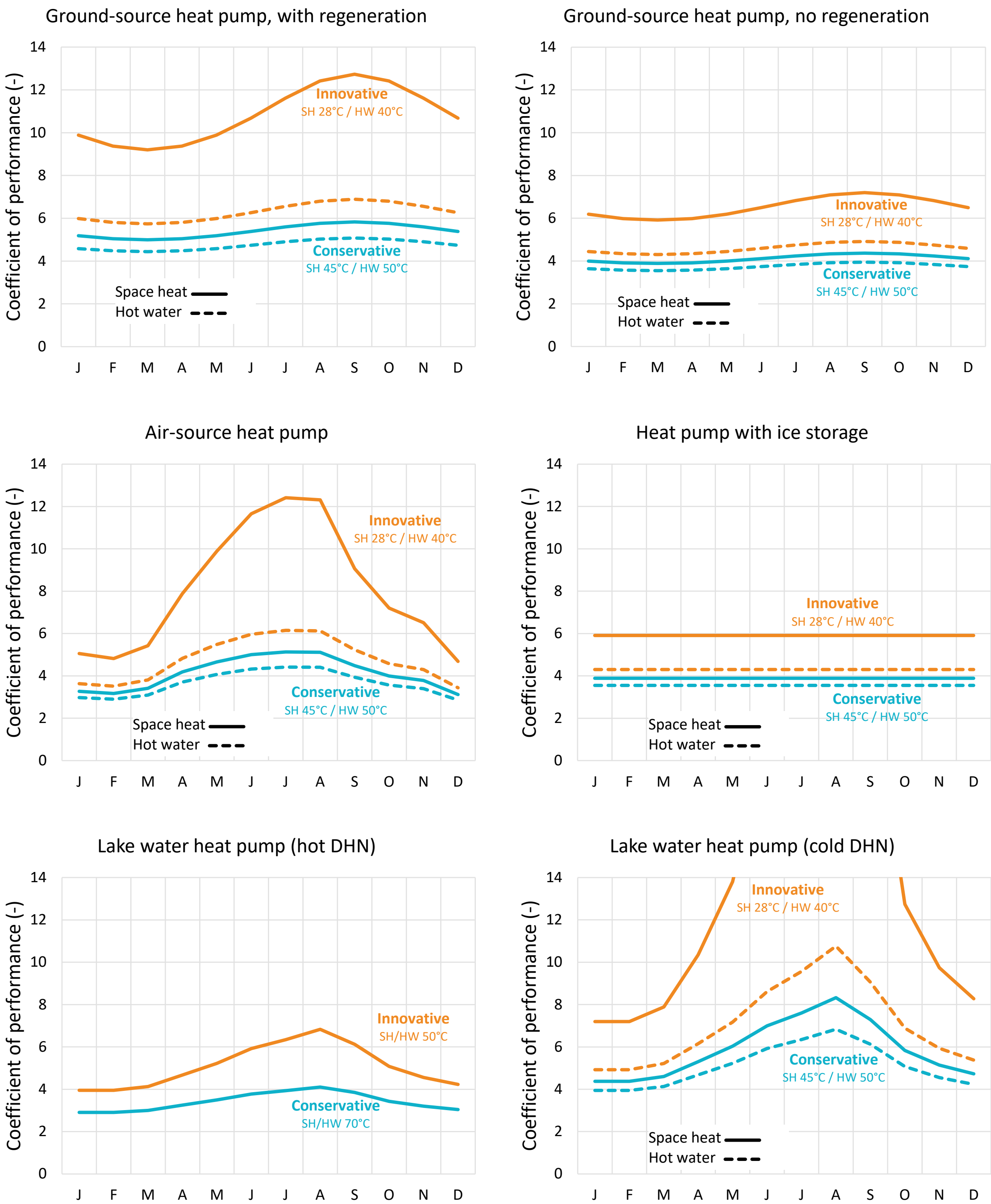


Figure 5: Seasonal variation of coefficient of performance for various types of heat pumps.

As shown in Figure 5 we also distinguish two types of heating networks that draw heat from a lake. In the traditional case a large heat pumps takes anergy from a lake and delivers heat at high temperature via the thermal network to the customers. In the second case we model a 5GDHC network where distributed heat pumps deliver heat to the buildings. The first case requires active cooling by electrical chillers, the second case allows for free cooling.

# 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 and also the less ambitious targets from 15, 18, 21 and 24 $Mt_{CO2}$/a. On top of these 36 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.

## 4.1 Electricity production and consumption

Figure 6 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 7 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.

The figures 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. Figure 8 shows time series for electricity generation and consumption for a case that is close to the median of the statistical distributions shown previously. We choose the intermediate climate target (Domestic, 6 $Mt_{CO2}$/a). It uses 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 pumped hydro 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. As further detailed in Section 5.5, we assume a maximum charging power of 5 GW that is actually fully used in summer during the day. The next technology that can use PV overproduction is heat pumps and electric heaters ⑤ although in the base scenarios their role is rather limited. Especially electric heaters become more important once the flexibility of electric vehicle charging is limited (see again Section 5.5). The last technology that can in principle utilize summer PV generation is hydrogen electrolysis. It appears only the Alone/Conservative scenario. Sections 6.1 and 6.2 explore cases where electrolysis plays a larger role.

The insufficient generation of photovoltaics in winter is the second issue to be solved. As shown in Figure 8, power generation by thermal plants ⑥ and/or imports ⑦ 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.**

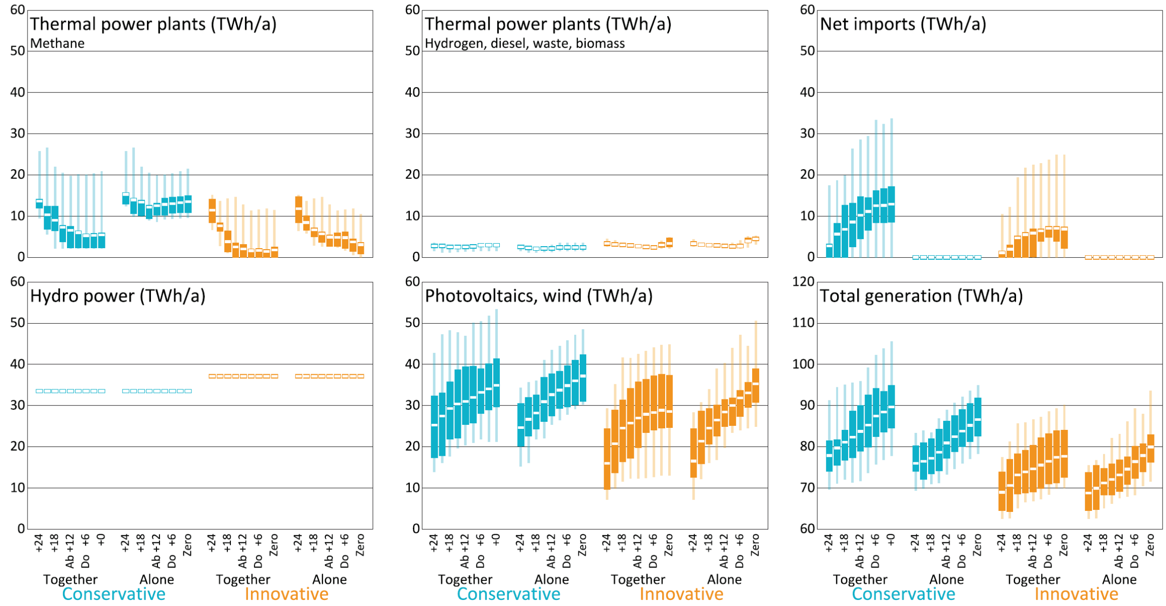


Figure 6: Electricity generation for base scenarios.

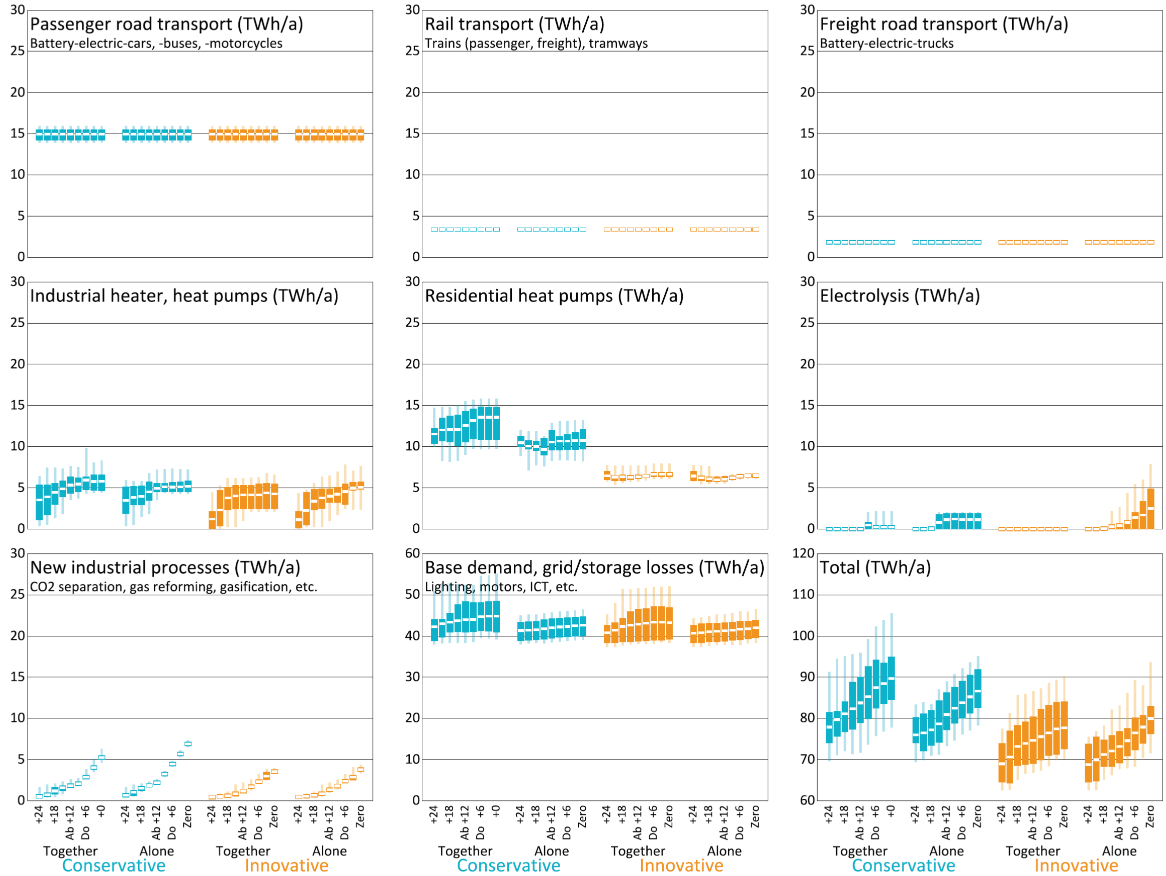


Figure 7: Electricity consumptions for base scenarios.

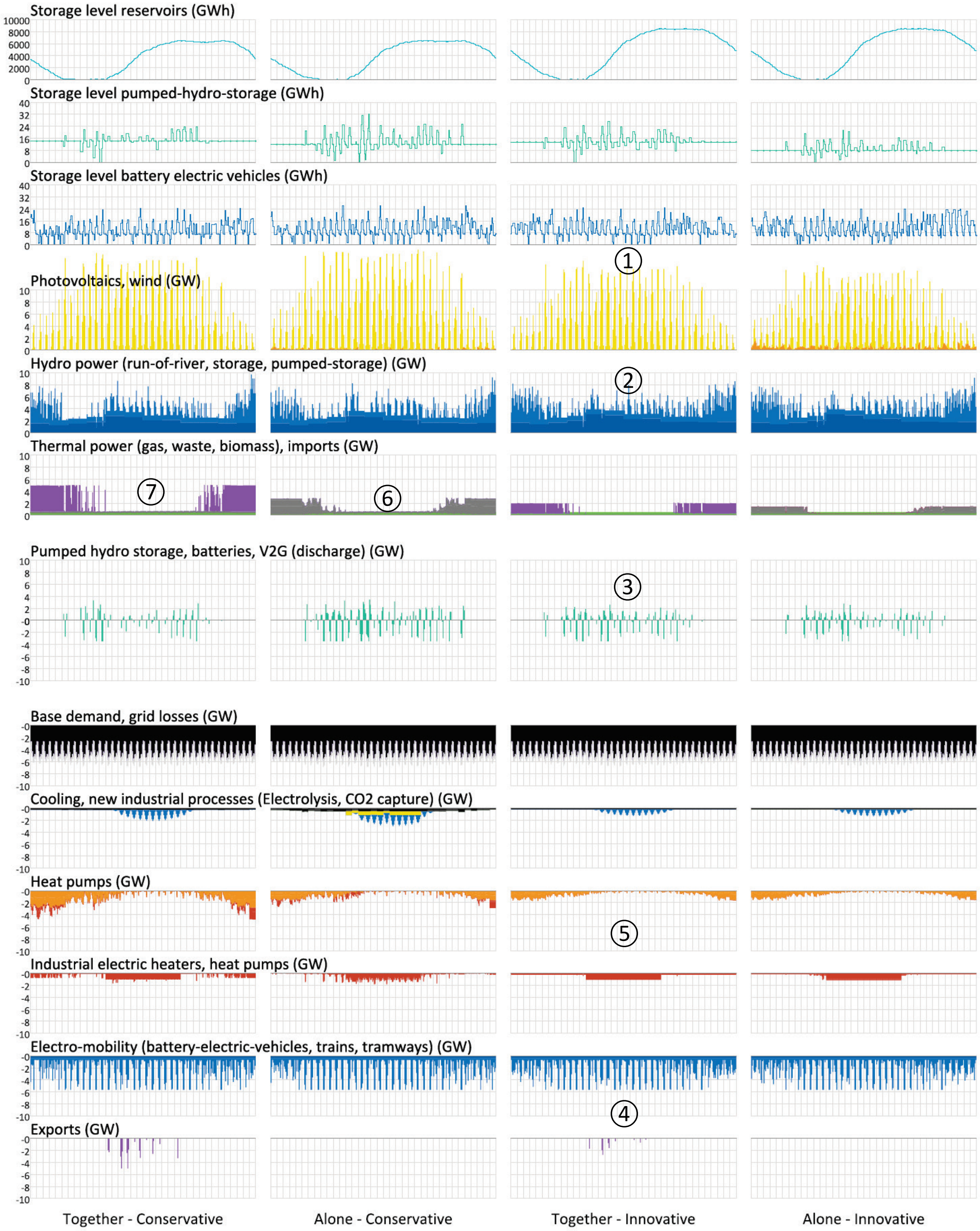


Figure 8: Electricity generation and consumption for a typical scenario at 6 $Mt_{CO2}/a$ (Domestic).

## 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 9 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. Note that the total heat supply is not constant since we consider renovation measures as a cost optimization decision.

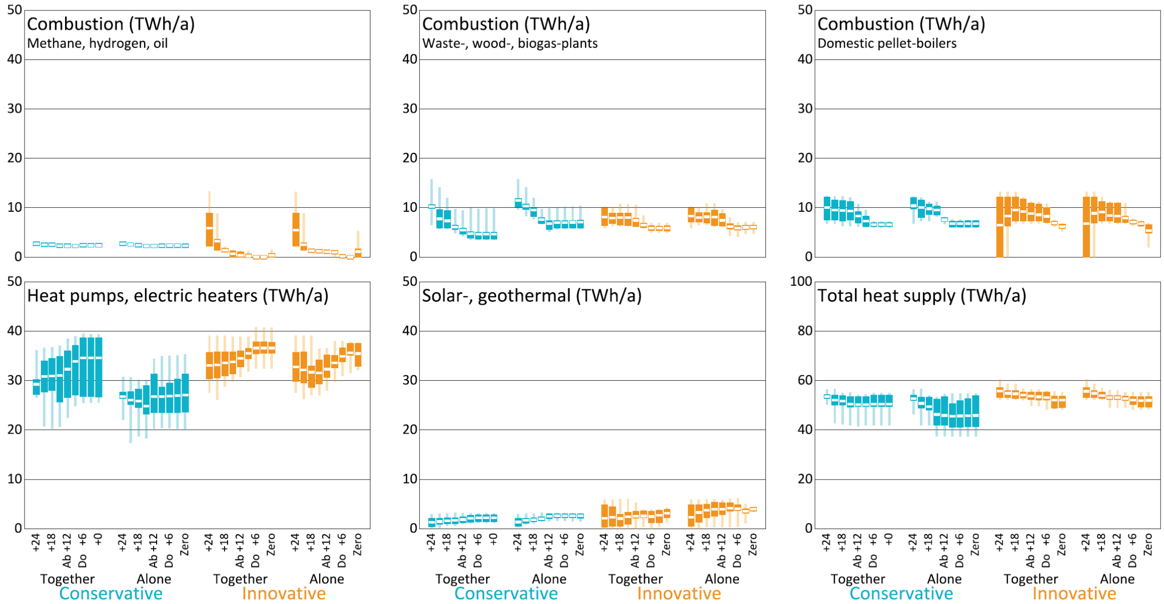


Figure 9: Space heat and domestic hot water supply for base scenarios.

## 4.3 Industrial process heat

As shown in Table 2 we split industrial process heat into three categories, namely intermediate, medium and high temperature heat. Intermediate temperature heat is assumed to be at approx. 100 °C and can be served by geothermal or solar thermal sources, and by CHP plants with 1 bar steam extraction (or back pressure). Medium temperature heat is at approx. 200 °C, it can be supplied by CHP plants with steam extraction (or back pressure) at 8 bar and by solar/geothermal via high temperature heat pumps with a COP of 2. Finally, high temperature heat is above 200 °C and it requires direct combustion of a gaseous, liquid or solid fuel. On all temperature levels there is the additional option of direct electrical heating. Not having a detailed distribution of heat demand vs. temperature level we assume a split of 25%, 25% and 50% for intermediate, medium and high temperature heat, respectively

Figure 10 shows the sources of intermediate temperature process heat. In the Innovative scenarios this is supplied by geothermal energy. In the Conservative scenarios there is a mix of solar thermal, direct electricity and gaseous/liquid CHP plants with steam extraction. Note that solar thermal requires some thermal storage, therefore the total heat generation is higher for these cases. Figure 11 shows the sources of medium temperature process heat, there is a mix of CHPs, direct electric heating and solar/geothermal via heat pumps. The 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. The supply of high temperature process heat is shown in Figure 12. Again, there is a mix of combustion of gases, liquids and solid, and direct electricity. The same picture can be seen in Figure 13 where all temperature levels are added up. Ther is no clearly dominating source of process heat, combustion, direct electrical heating and also new sources like solar- and geothermal all have a similar share.

As shown later in Section 4.6, the net-zero goal requires some level of CO2 separation and storage. Separating CO2 from flue gases of combustion systems is often realized via an amine scrubbing process. This requires roughly 1 MWh/$t_{CO2}$ of heat at approx. 100-150°C. Capturing CO2 from the atmosphere requires a larger amount of roughly 2 MWh/$t_{CO2}$ at approx. 100°C. Figure 14 shows the heat demand for these processes.

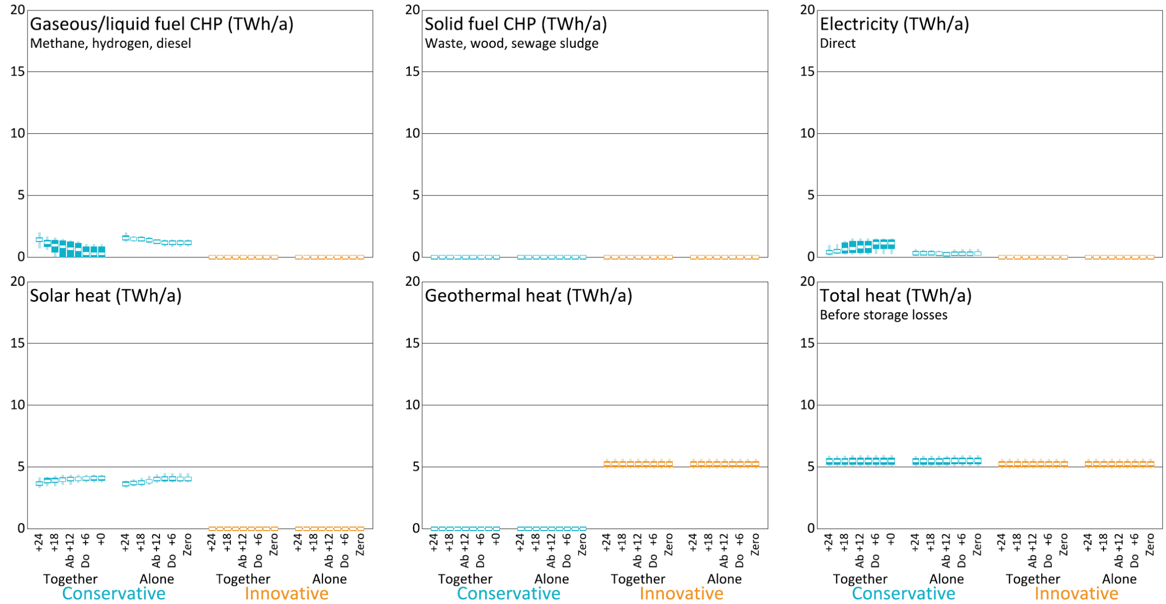


Figure 10: Supply of intermediate temperature industrial process heat for base scenarios.

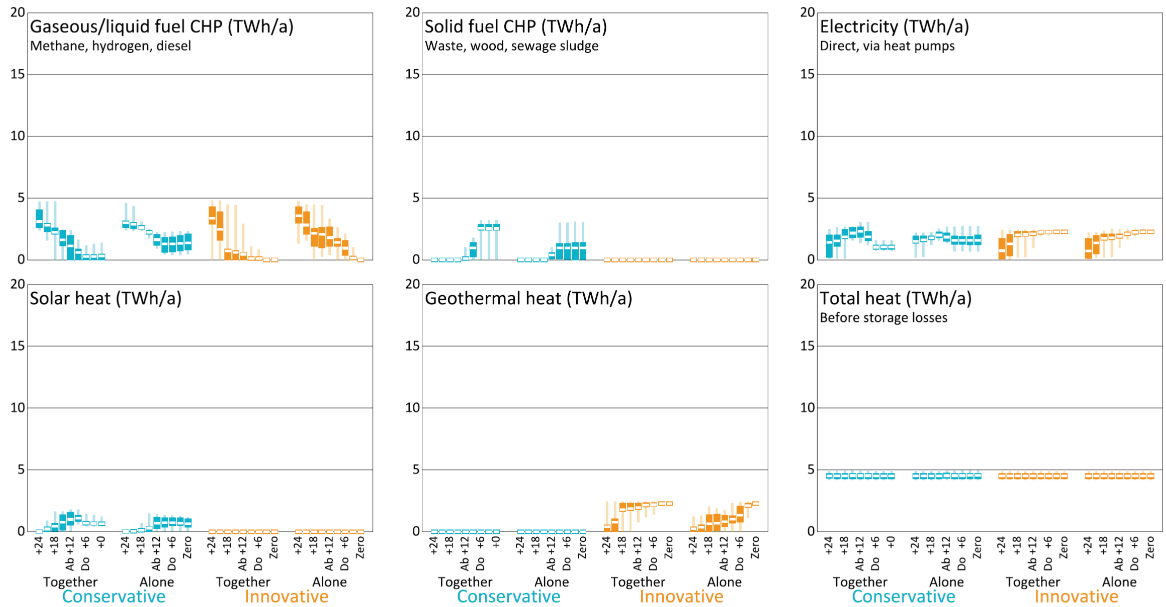


Figure 11: Supply of medium temperature industrial process heat for base scenarios.

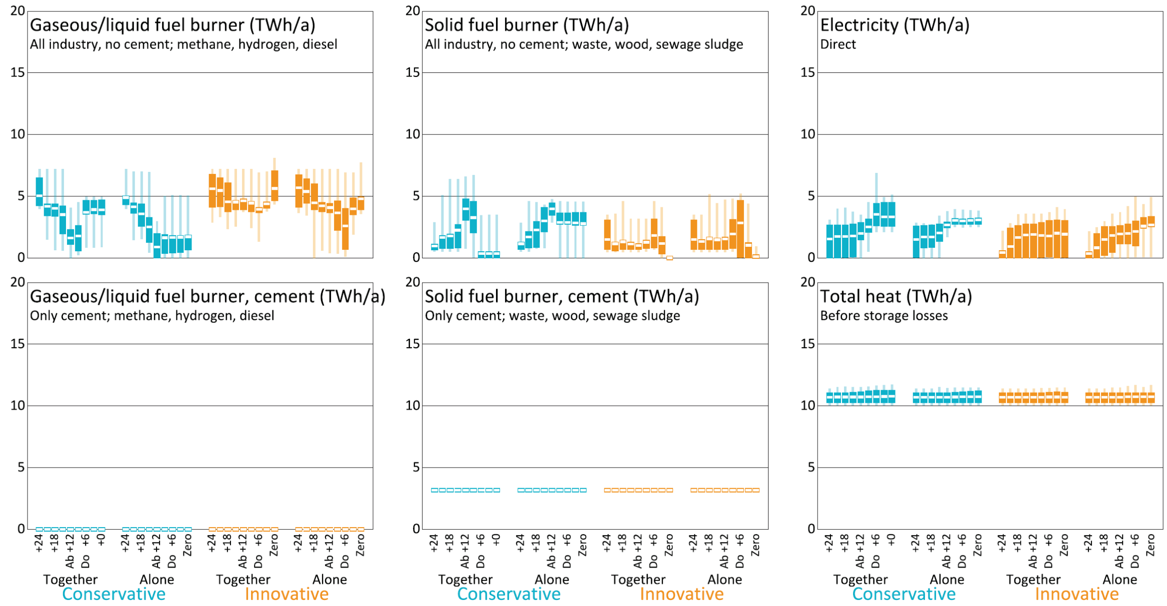


Figure 12: Supply of high temperature industrial process heat for base scenarios.

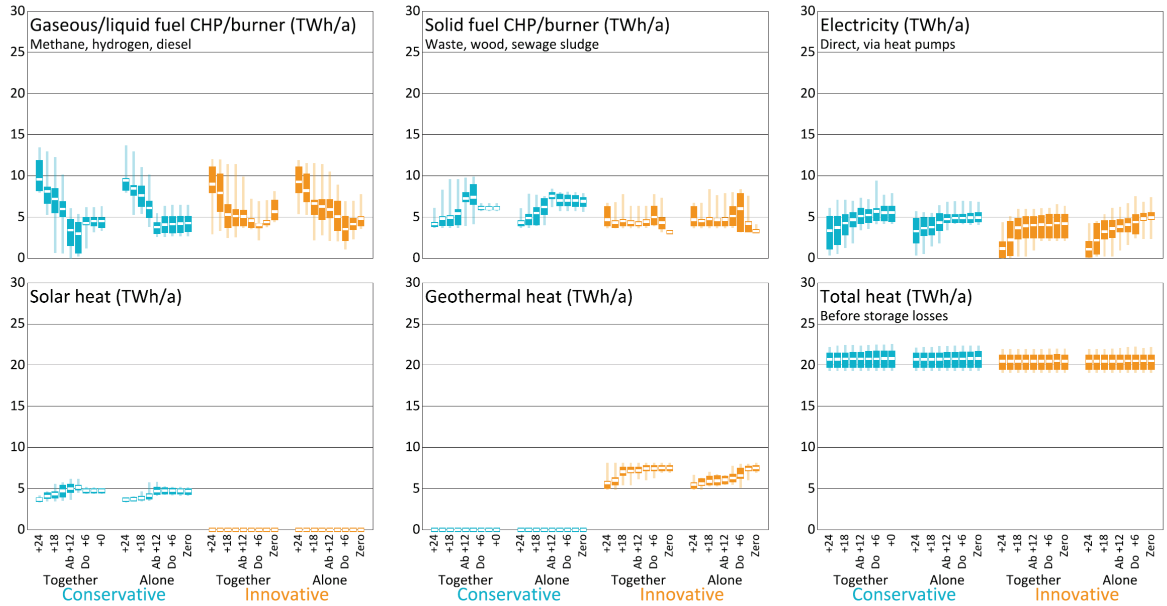


Figure 13: Total supply of industrial process heat for base scenarios.

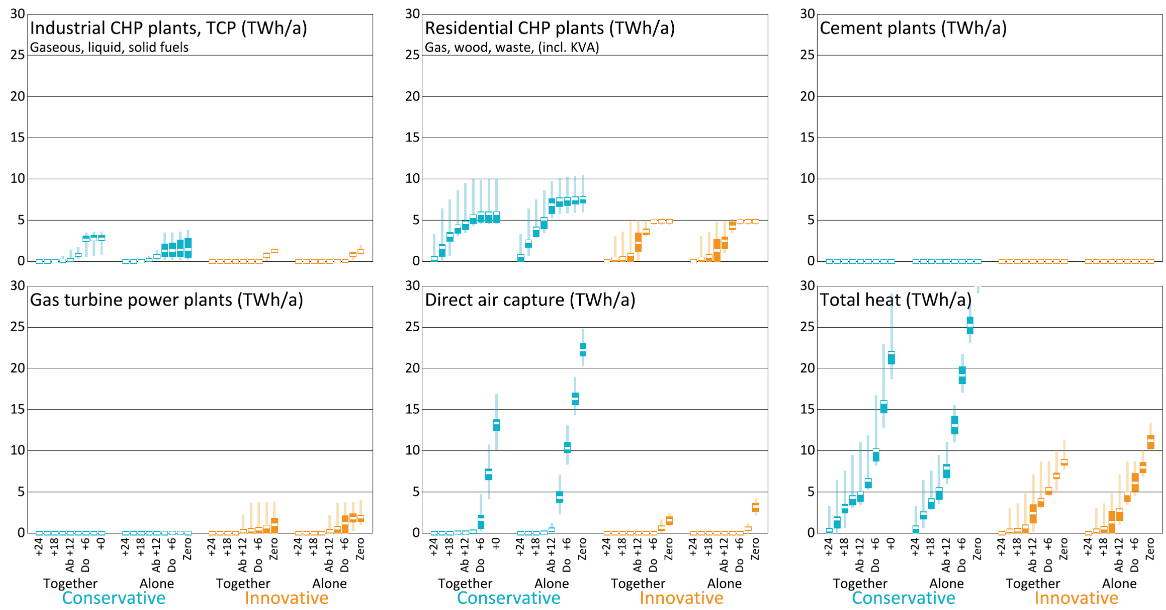


Figure 14: Additional consumption of process heat for CO2 separation (from flue gases and air) for base scenarios.

## 4.4 Production and consumption of solid, liquid and gaseous fuels

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), as well as the use of waste and wood.

Figure 15 and Figure 16 show 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 17 and Figure 18 show the supply and use of methane. Supply is dominated by imports, especially in the Conservative scenarios. Domestic generation by anaerobic digestion amounts to 4-5 TWh/a. Here we have to distinguish a situation where the biogas is upgraded to bio-methane and fed to the gas grid (Innovative scenarios) or where is only can be used in a local CHP plant (Conservative scenario). These options are further explored in Section 5.3. 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 19). Interesting is the production of Diesel via hydrothermal liquefaction of digestate that delivers 4-5 TWh/a (see also Section 6.4). The use of liquid fuels (Figure 20) 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 16.

Figure 21 shows the use of wood for various purposes. For high CO2 targets the dominant use is for domestic heating and hot water. Moving towards net-zero this shares declines and is shifted to higher value applications such as industrial combustion or gasification and liquefaction. Note that also the use of wood as construction material is beneficial for reaching the net zero targets (see also Section 5.6). The dominant use of waste is in waste-to-energy plants that deliver space heat and domestic hot water via district heating networks, all the rest is used for industrial combustion, especially in cement plant (see Figure 22). This high share of waste-to-energy plants is imposed as a constraint, considering that these plants are present today and will not disappear until the middle of the century. However, it is interesting to explore how an optimal use of waste as a resource would look like if it could be used freely (see Section 6.5).

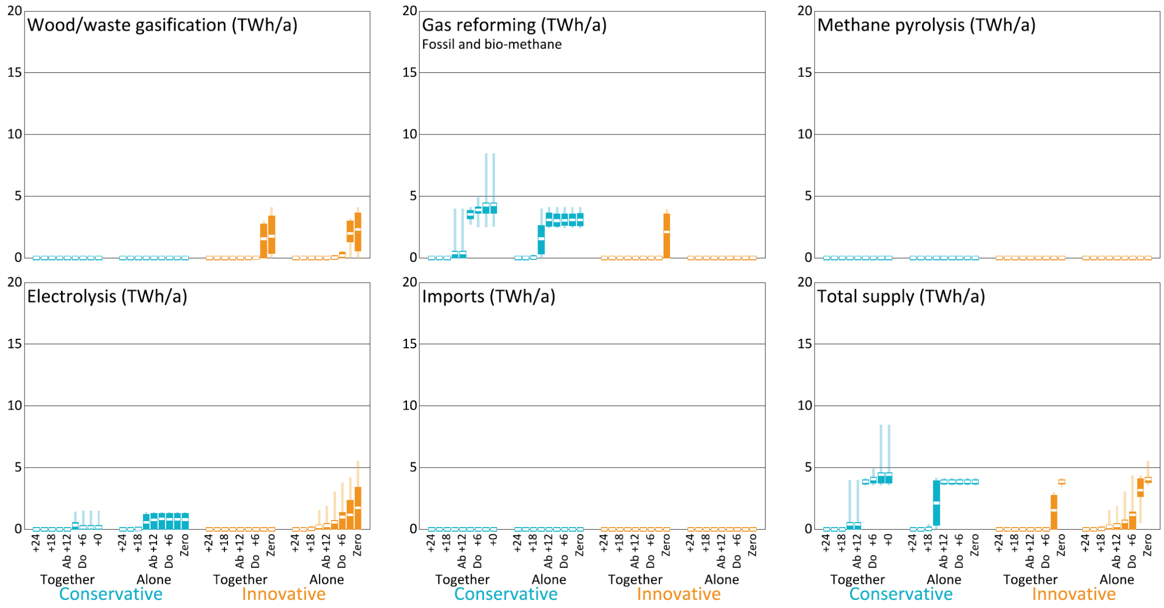


Figure 15: Supply of hydrogen for base scenarios.

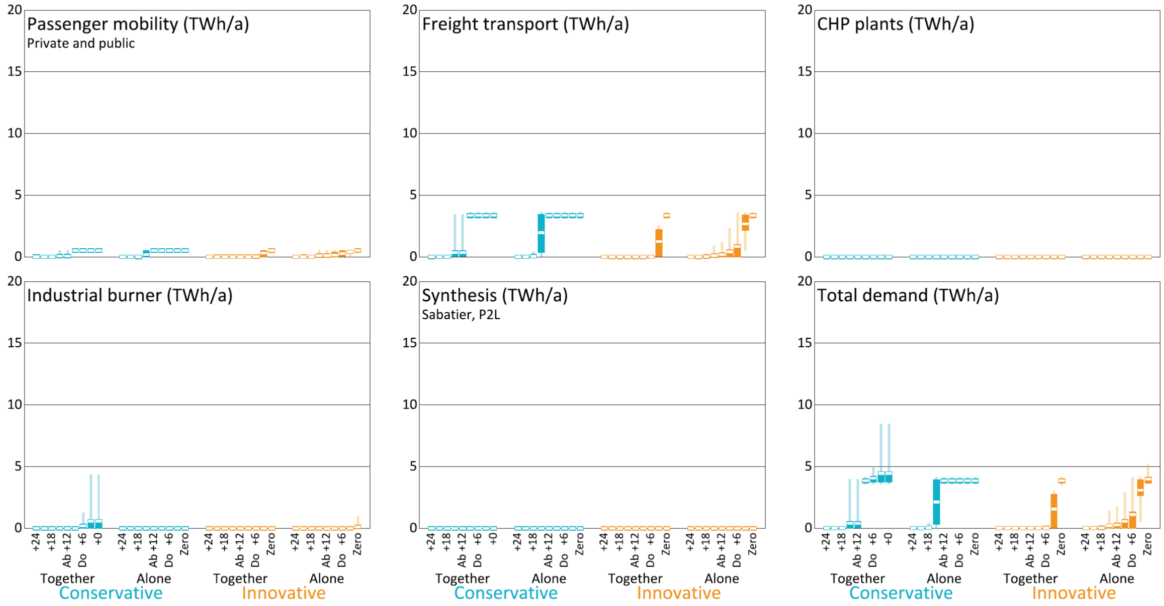


Figure 16: Demand for hydrogen for base scenarios.

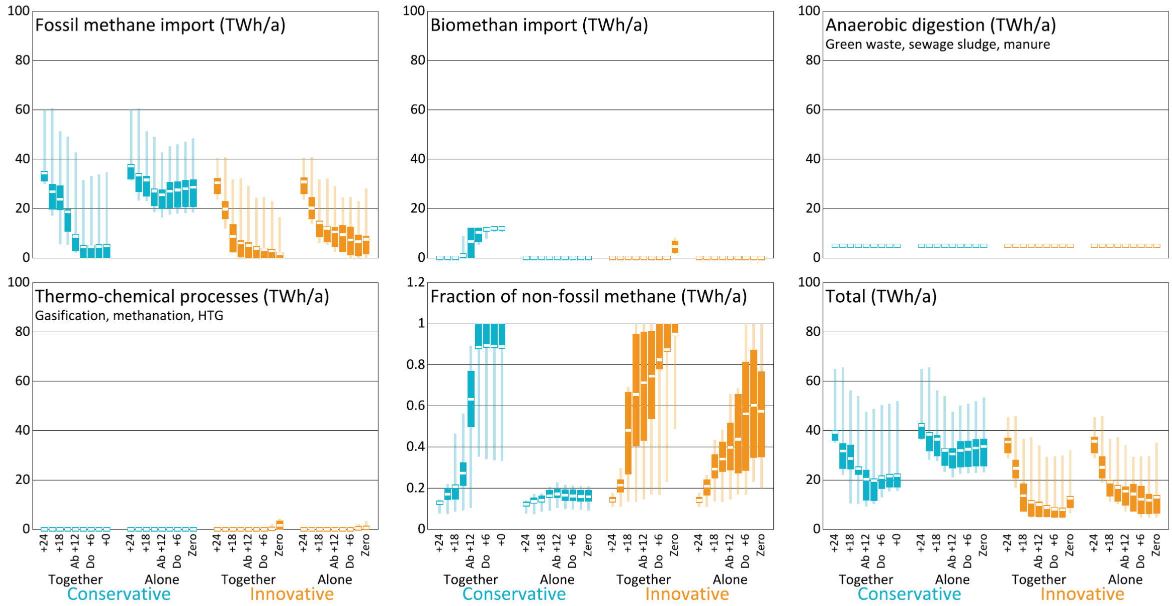


Figure 17: Supply of methane (incl. not upgraded biogas) for base scenarios.

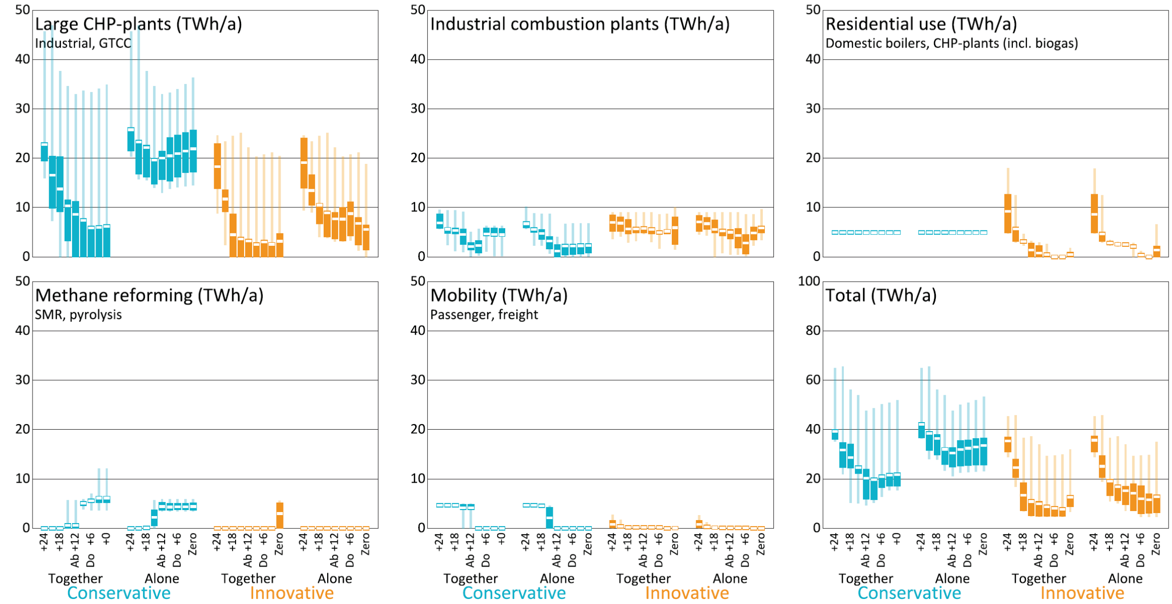


Figure 18: Demand for methane (incl. biogas directly used in rural CHP) for base scenarios.

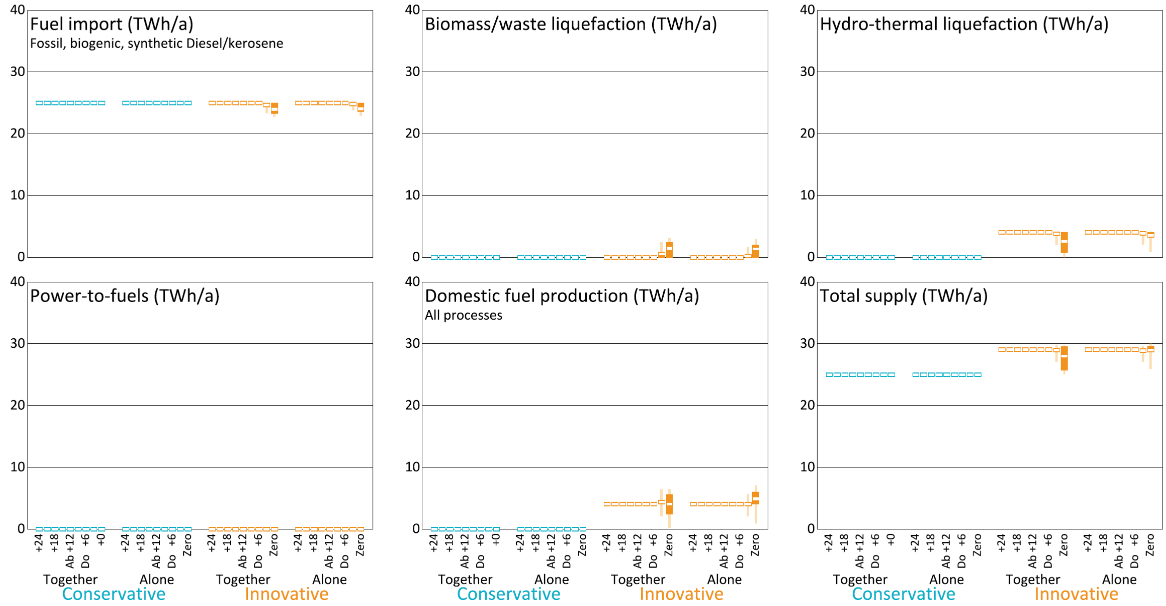


Figure 19: Supply of liquid fuels for base scenarios.

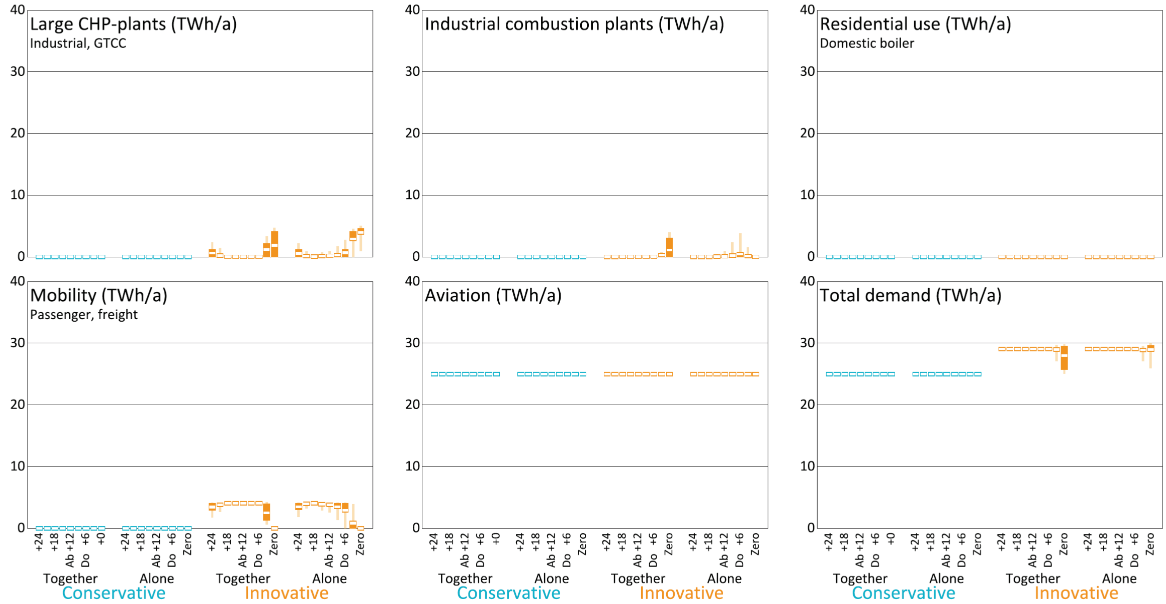


Figure 20: Demand for liquid fuels for base scenarios.

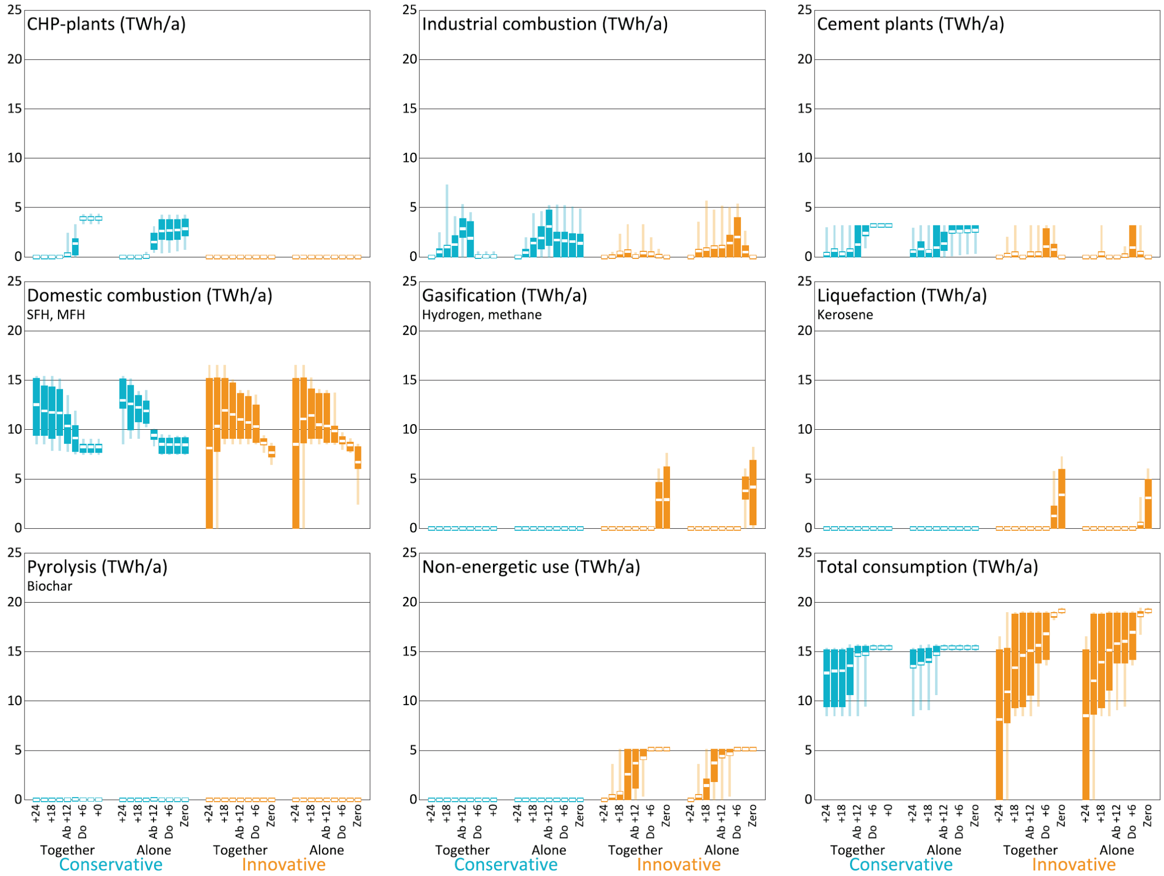


Figure 21: Demand for wood for base scenarios.

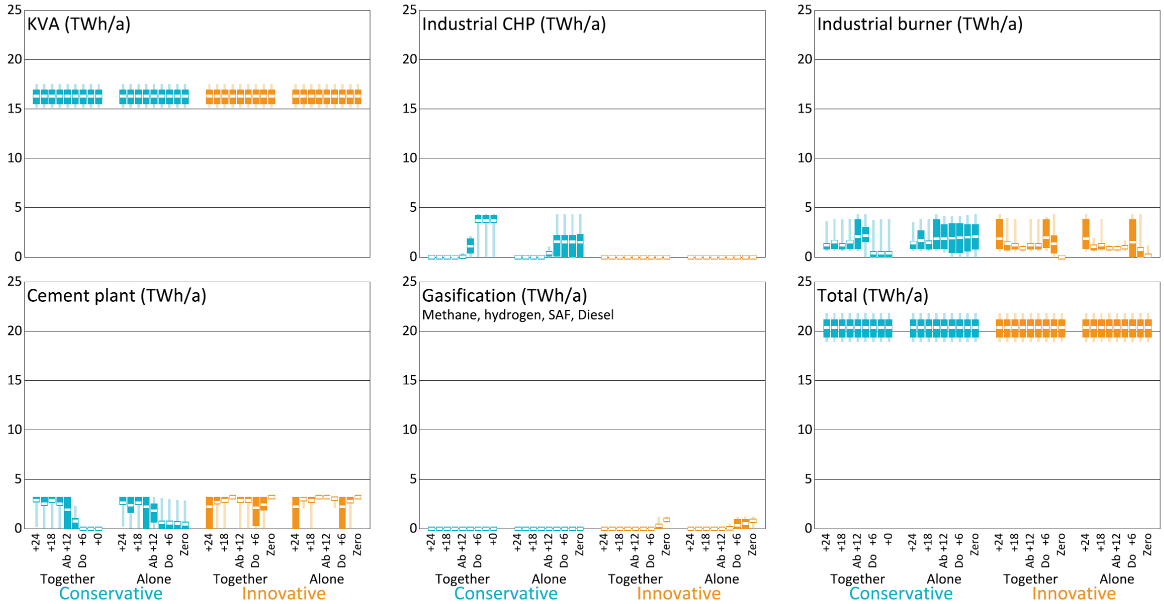


Figure 22: Demand for waste for base scenarios.

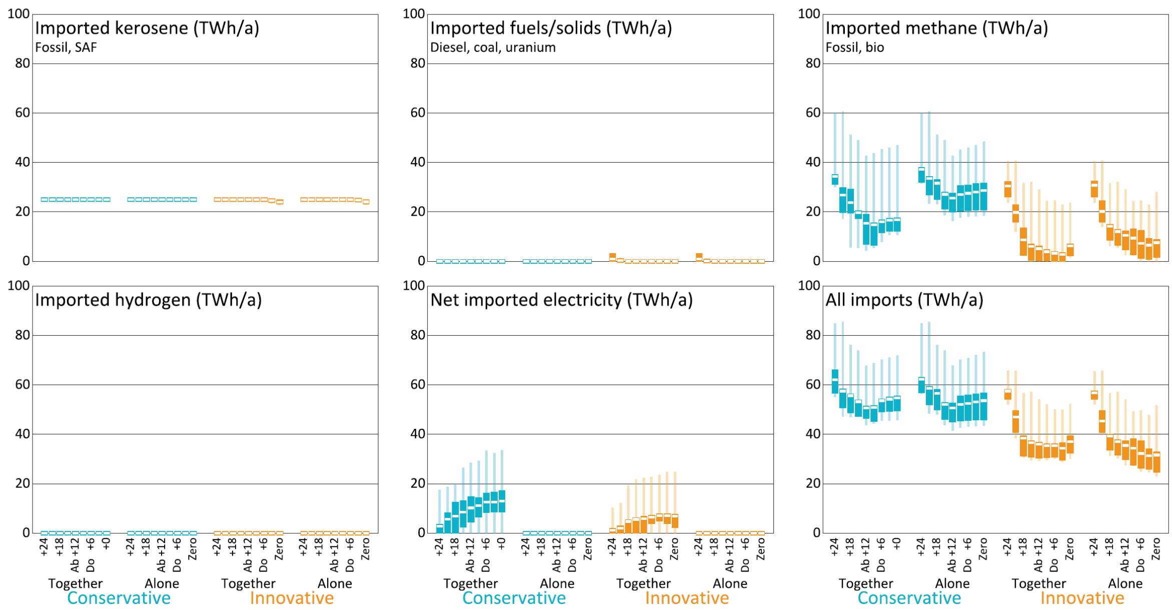


Figure 23: Primary energy imports for base scenarios.

## 4.5 Primary 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 23 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 $CO_2$ separation, usage and storage

It is understood that besides the electrification of the demand sectors heating and mobility, it is also necessary to permanently remove CO2 from the biosphere. CO2 may be separated from point sources or from the atmosphere using direct air capture. Point sources are combustion processes, gasification or also biological processes like anaerobic digestion. CO2 may then be stored underground which will most likely require the transport to a suitable storage location, or it may be used for the synthesis of carbon containing chemicals (e.g. sustainable aviation fuels). An equivalent CO2 storage may also be achieved by pyrolysis processes that deliver biochar that can be stored as a solid in the ground, or in the form of wood in the construction sector. Our results allow to quantify the importance of the aforementioned options. Figure 24 shows the sources of separated CO2, that can then be either used or stored. Figure 25 shows that CO2 usage is not an option, instead, all CO2 is permanently stored. The necessary amounts are some 10-15 Mt/a for the domestic scenario where net-zero has to be achieved in Switzerland. Figure 26 shows that in addition to the storage of CO2 as a gas some equivalent storage is realized in the innovative scenario by using wood as a construction material. Biochar plays only a minor role.

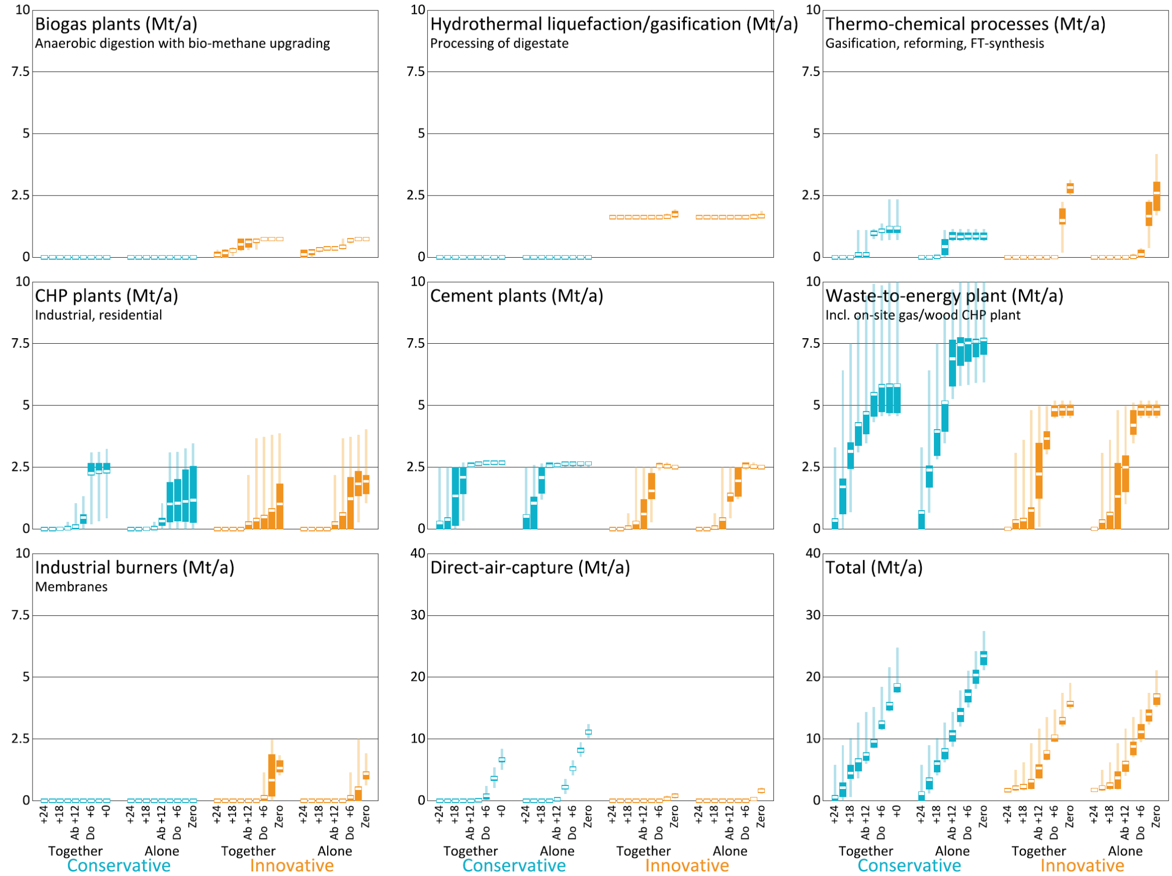


Figure 24: CO2 separation for base scenarios.

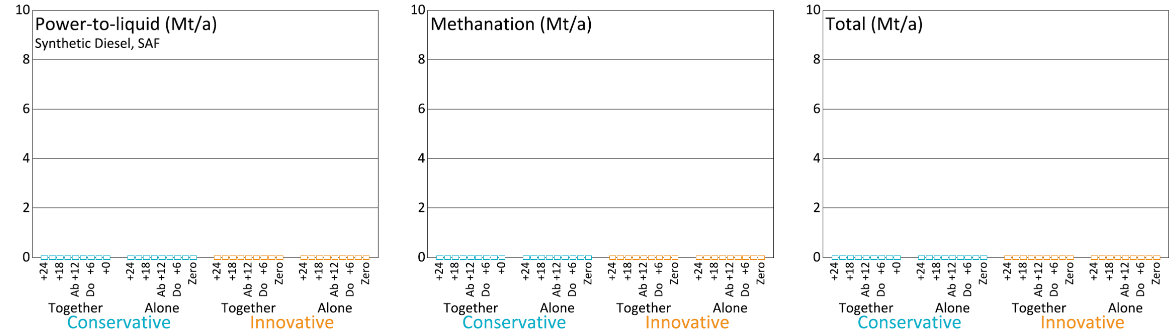


Figure 25: CO2 usage for base scenarios.

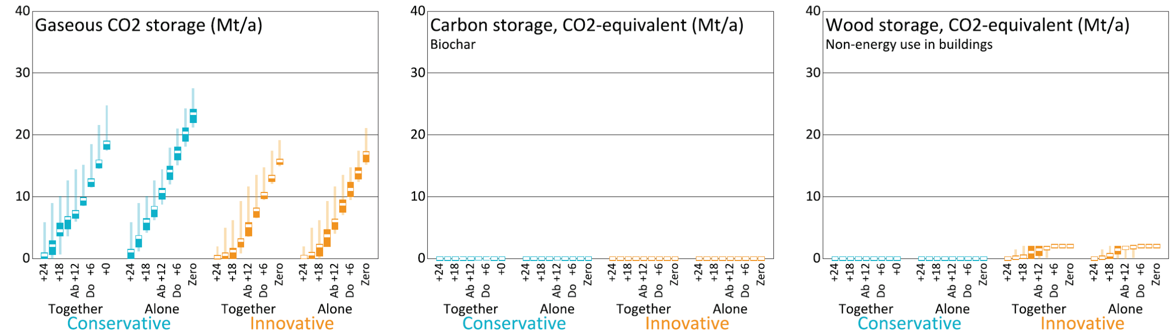


Figure 26: CO2 storage for base scenarios.

## 4.7 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 27 (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 24 Mt/a, this marginal avoidance cost eventually reaches zero. This can be interpreted as the optimal system configuration if $CO_2$ emissions had no price, i.e. the state where a business as usual scenario would settle.

The right side of the figure shows the absolute total system costs These are the integral of marginal costs (and the marginal costs the derivative of the total costs). As explained in Section 3, the $CO_2$ target of +6 Mt/a (Domestic) represents the true net-zero to strive for. Figure 27 shows that the extra costs between a CO2 target of more than 24 Mt/a and net-zero 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.

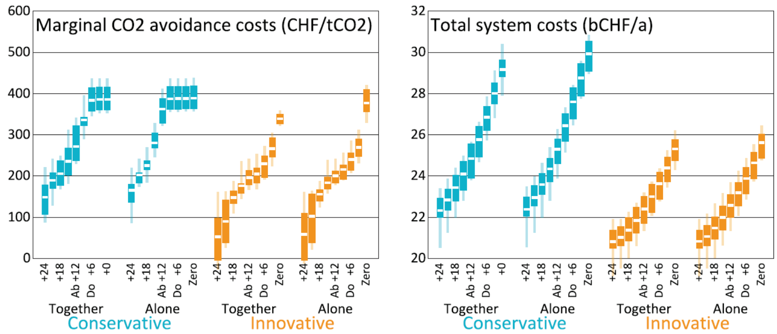


Figure 27: Marginal $CO_2$ avoidance costs and total system costs for base scenarios.

## 5 The value of innovative technologies

As shown in Section 3, Table 3, we defined innovative and conservative scenarios that differ by a large number of options such as the availability of alpine PV, seasonal thermal energy storage, etc. This section highlights the value of some of these technology options in the context of reaching the net-zero goal. We do this by *adding* a given technology to the conservative scenarios and by *removing* it from the innovative ones. It can be expected that this process is not symmetric, i.e. the disadvantage of not having one out of many innovative technologies is probably smaller than the benefit of having only this single one. This effect will be seen throughout this section.

In order to visualize the benefit of innovative technologies we repeat selected figures from Section 4 by showing the variation and compare it to the baseline scenarios. We also show one additional type of figure that displays the difference in total energy imports and the difference in total system costs, i.e. two quantities that are relevant in the discussion of the energy transition. Figure 28 shows this for a situation where all innovative technologies are removed from the innovative scenarios and added to the conservative one, essentially the difference between innovative and conservative. Since we switch all technologies, the aforementioned asymmetry is not present. Generally, it can be seen that the value of innovation is huge, both in regards of import dependency and total system costs.

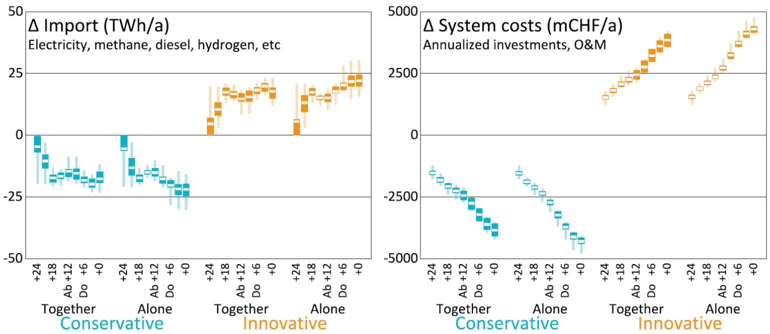


Figure 28: Variation of imports and total system costs when flipping innovative and conservative scenarios.

## 5.1 Innovative heating systems

An important objective for the past year was an improved representation of heating systems in SES-ETH. As explained in Section 3.1 this includes (i) a better representation of the coefficient of performance (COP) of heat pumps under various conditions, (ii) the explicit simulation of cooling needs, (iii) the separation of heating networks in low temperature grids with distributed heat pumps that allow for free cooling (5$^{th}$ generation district heating & cooling networks, 5GDHC) and high temperature grids with one large heat pumps, and (iv) the modelling of regenerated vs. non-regenerated boreholes for ground-source heat pumps. This section gives an overview, how these innovations impact the overall energy system

While it is undisputed that heat pumps will deliver the largest share of space heat and domestic hot water for buildings (see Figure 9), it is often overlooked that the electricity demand of heat pumps can be influenced significantly by ensuring that the source and sink temperatures are as high and as low as possible, respectively. As a first innovation we consider the effect of low temperature heat supply in buildings. In the pre-heat pump era, space heat was generated by combustion. Delivery temperature could be as high as needed for the traditional distribution systems via radiators, usually some 60-70 °C. Today's standard system is underfloor heating where the delivery temperature is in the order of 40-45 °C which can be reached easily by heat pumps. Alternatively, convective systems use large surface heat exchangers with fans to supply heat at minimal temperature difference. Here the delivery temperature may be as low as 25 °C.

As explained in Section 3.1, we assign heat pumps with a low-temperature heat supply system to the innovative scenario and the traditional underfloor heating to the conservative scenario. We now switch this feature between the innovative and the conservative scenarios, i.e. we recalculate everything with innovative scenarios having underfloor heating and the conservative scenarios having low-temperature supply systems. This allows to isolate the effect of supply temperature on the overall energy system. Figure 29 shows the effect on the supply of space heat and domestic hot water. Obviously, the share of heat pump increases once the conservative scenarios have low-temperature supply systems available ①. On the contrary, in the innovative cases with low-temperature supply systems, the share of heat pump decreases and more heat is delivered by combustion systems ②. This has a visible impact on the demand for electricity (see Figure 30), most notably for residential heat pumps ③. Figure 31 and Figure 32 show the same indicators for the availability of borehole regeneration and 5GDHC networks. The trend is similar, a larger share of heat pumps once this innovation is available and a reduction of electricity demand. Figure 33 and Figure 34 show the results for both innovations combined. It can be seen that the positive effects of innovation are roughly additive.

Figure 36 to Figure 38 show the impact of the various innovations in the heating domain on two relevant indicators, namely the total imports and the total system costs. Clearly, both imports and costs are reduced once the heating innovations become available in the conservative scenarios and vice versa for the innovative ones.

The most remarkable result is seen in Figure 34, where the total electricity demand is reduced by 5-10 TWh/a ④ once these innovations in the heating domain become available for the conservative scenario. This requires some extra explanation. Figure 35 shows the electricity generation of (non-thermal) renewables (top), extra generation by thermal power and imports (mid), and the demand for residential heat pumps (incl. cooling, bottom); for the summer half (left), the winter half (mid) and the full year (right). What is shown is the difference between the scenarios where all heating innovations are available in Conservative/not available in Innovative and the base scenarios.

In the summer half there is a lower production of renewables (mostly photovoltaics) in the Conservative scenarios once the heating innovations are available ⑤. This reduction matches approximately the reduced demand for heat pumps, in this case largely for cooling that is now possible using free cooling options instead of electrically driven chillers ⑥. The extra generation by thermal power shows little change, simply because the generation is low in summer. In winter, the conservative scenarios show again a lower production from non-thermal renewables that matches the reduction in summer. Remarkable is the reduction of extra generation by thermal power and/or net imports ⑦. Again, the sum of this reduced generation matches the lower demand for heat pumps which is a consequence of the combined heating innovations ⑧. The right column shows the same quantities for the whole year and again it is evident that the much lower generation is linked to the lower electricity demand by heat pumps. For the innovative scenarios that now lack all innovations in the heating domain, the changes are exactly in the opposite direction, i.e. more electricity is demanded by heat pump and therefore more electricity has to be provided by all generators.

**To conclude, innovations in the heating domain such as low-temperature heat distribution systems, 5GDHC networks or borehole regeneration have the potential to reduce the necessary extra generation by thermal power plants and/or net imports by 3-5 TWh/a of electricity. This addresses directly the so-called "winter gap problem".**

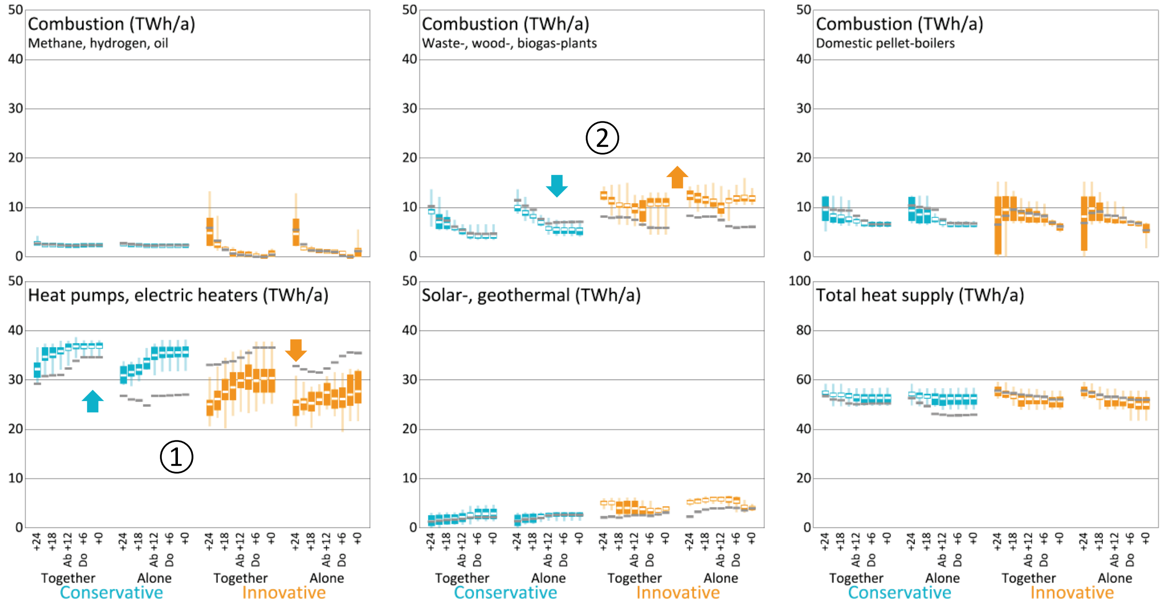


Figure 29: Supply of space heat and domestic hot water for base scenarios (median shown in grey) and new scenarios with/without low-temperature heat supply systems.

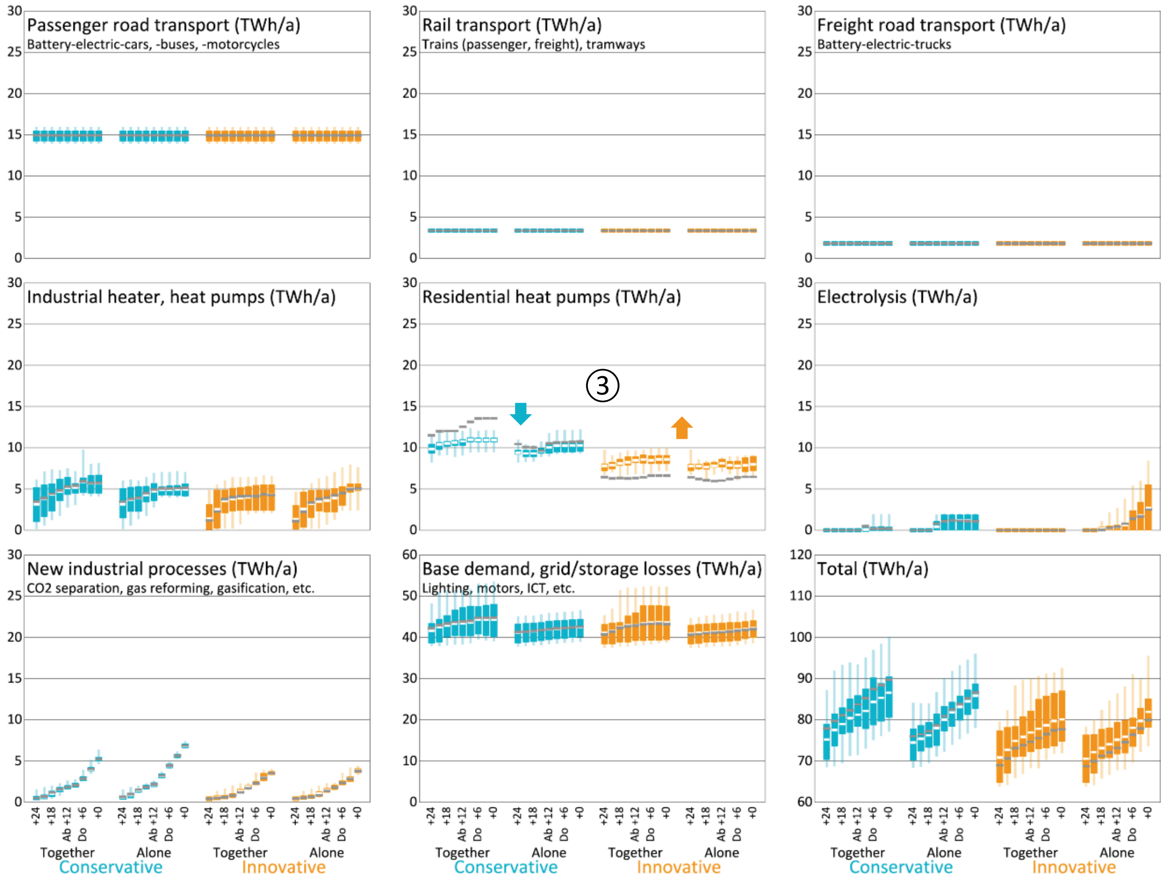


Figure 30: Demand for electricity for base scenarios (median shown in grey) and new scenarios with/without low-temperature heat supply systems.

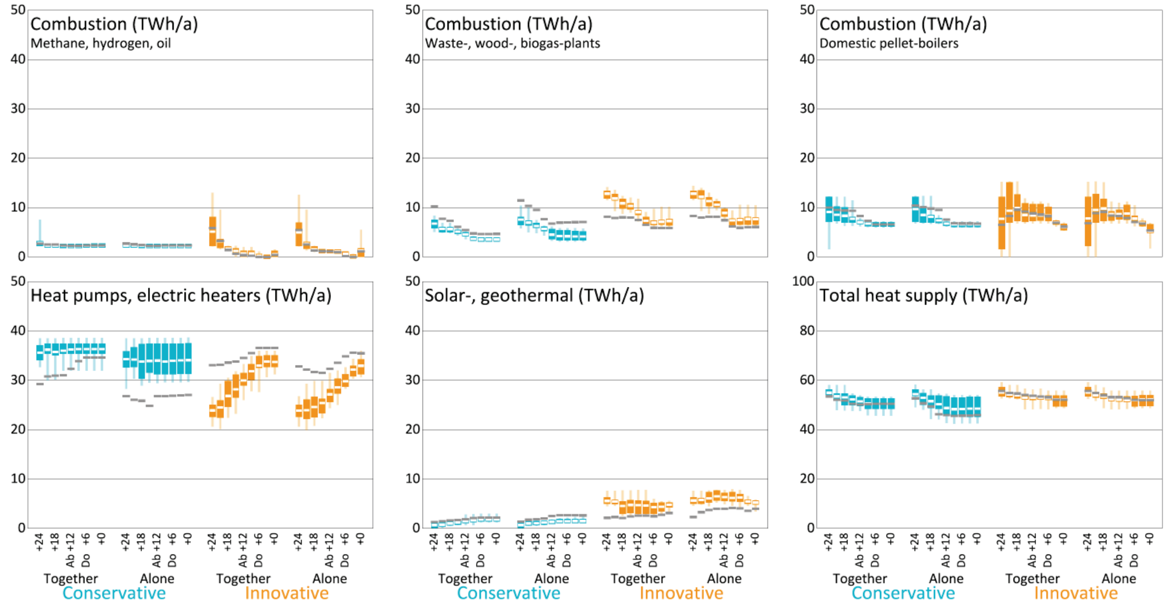


Figure 31: Supply of electricity for base scenarios (median shown in grey) and new scenarios <u>with/without borehole regeneration & 5GDHC networks</u>.

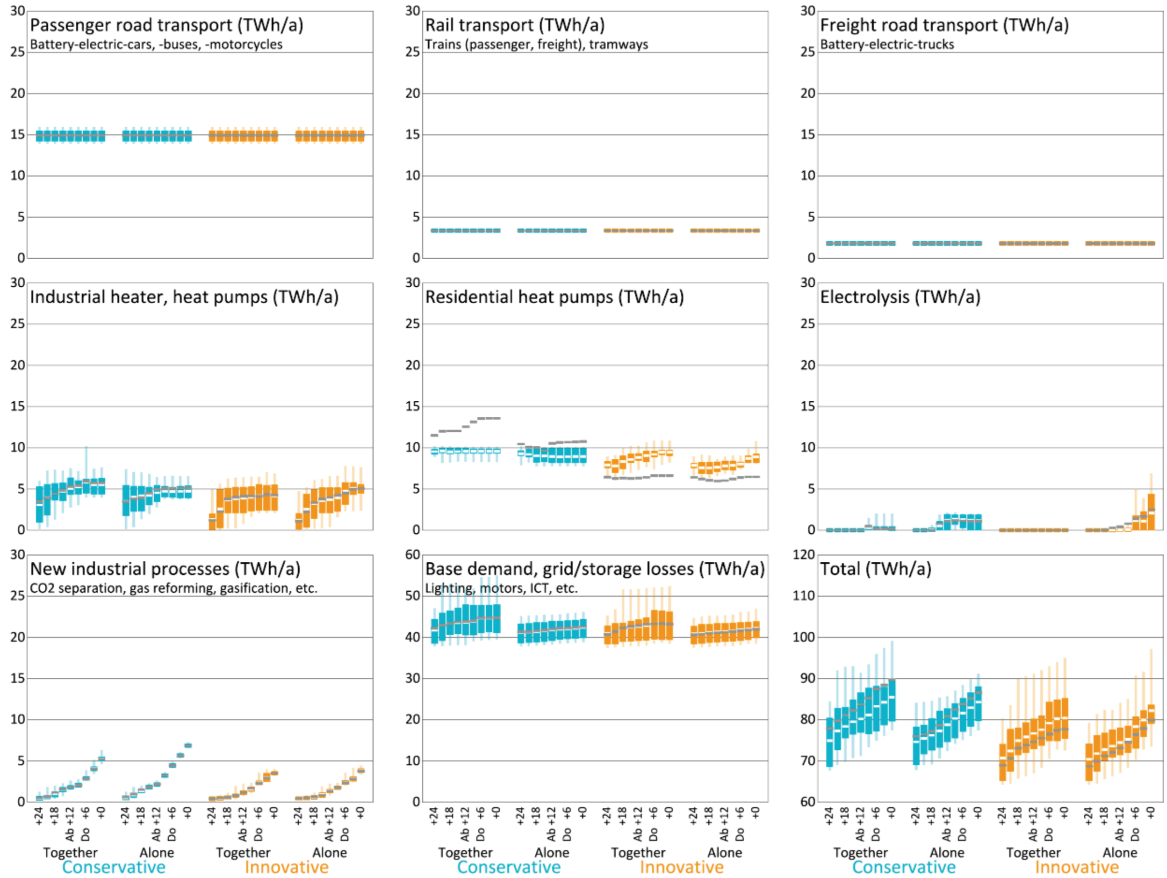


Figure 32: Demand for electricity for base scenarios (median shown in grey) and new scenarios <u>with/without borehole regeneration & 5GDHC networks</u>.

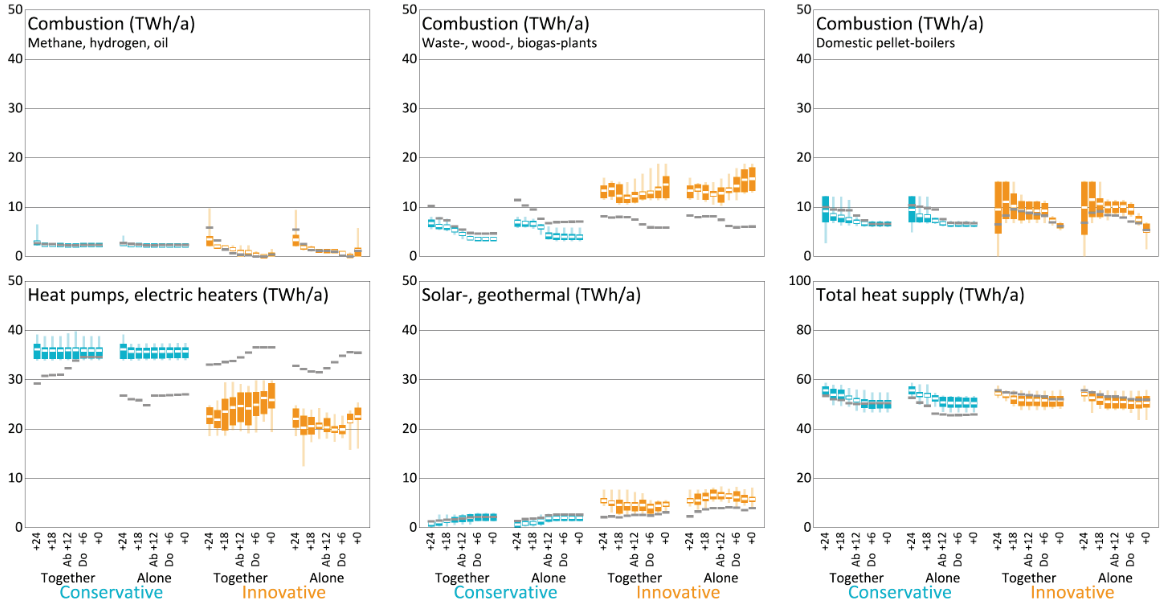


Figure 33: Supply of electricity for base scenarios (median shown in grey) and new scenarios <u>with/without combined heating innovations</u>.

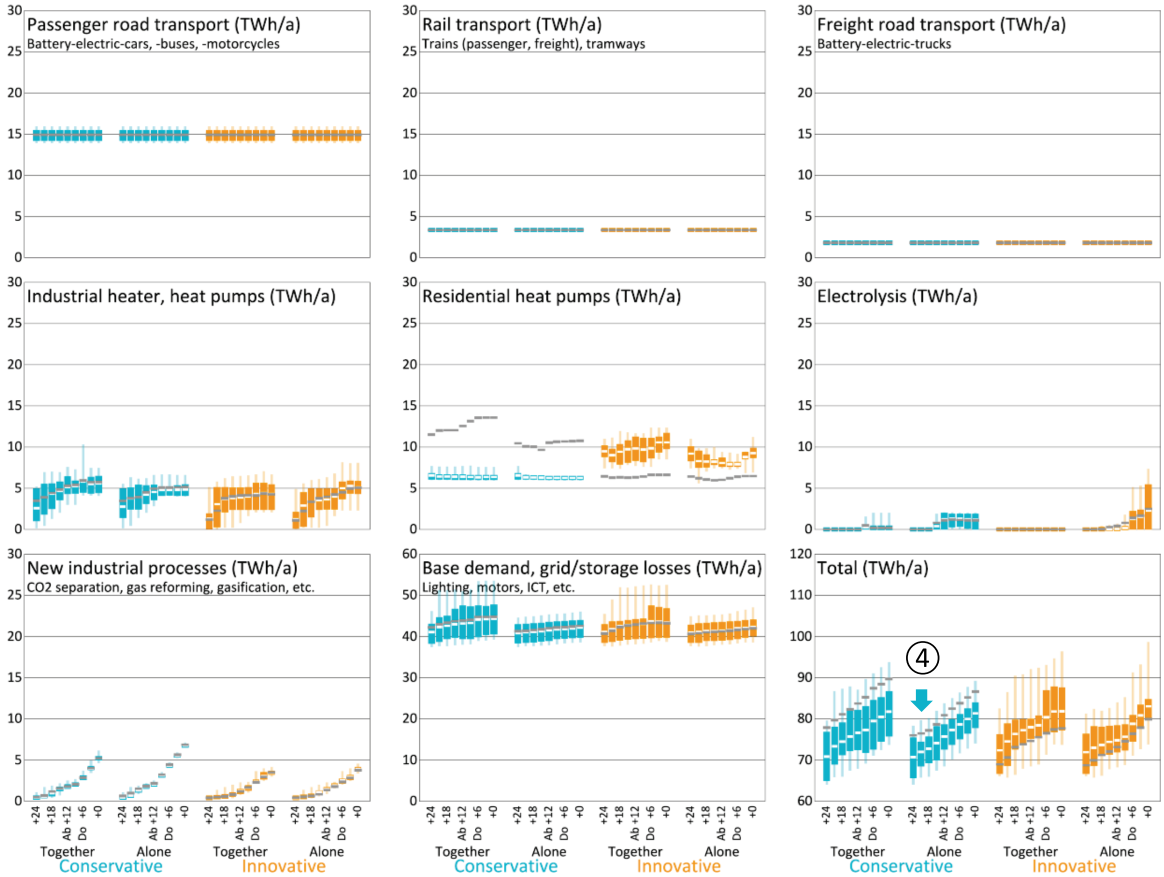


Figure 34: Demand for electricity for base scenarios (median shown in grey) and new scenarios <u>with/without combined heating innovations</u>.

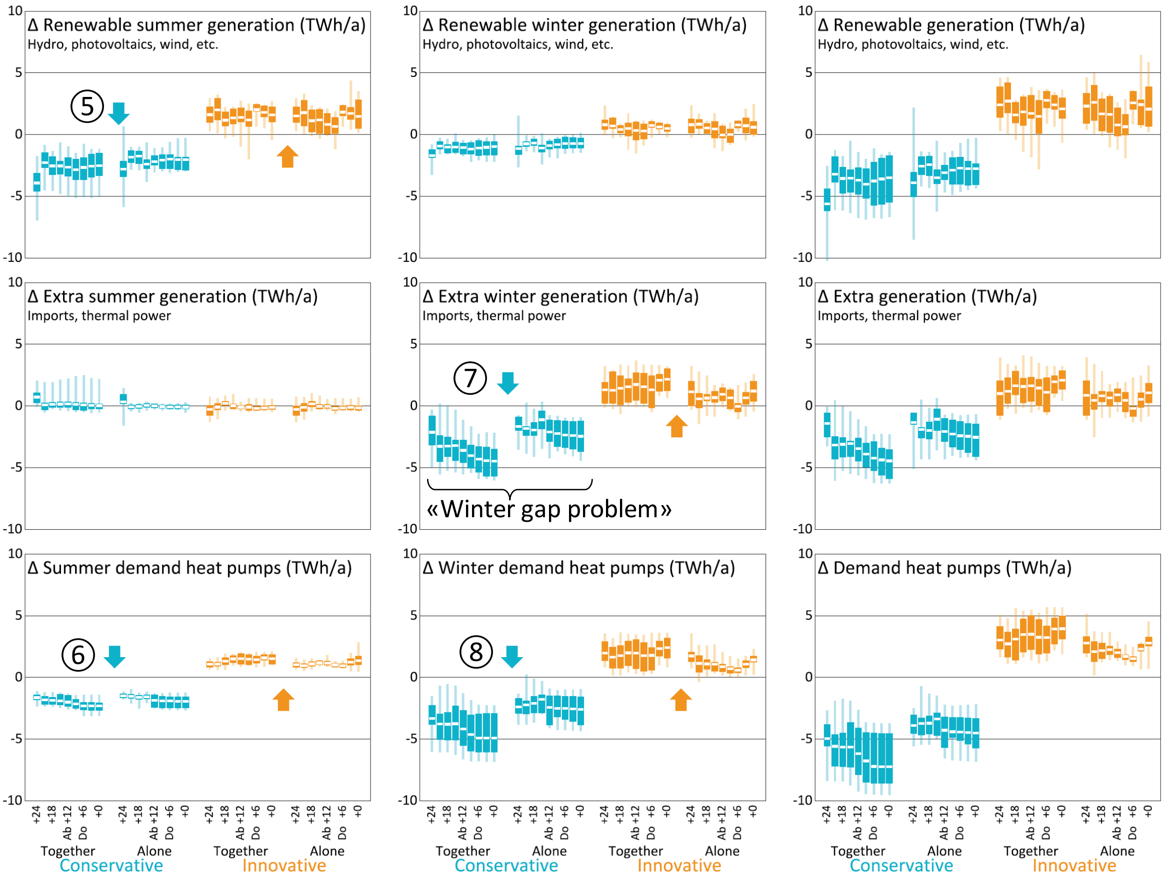


Figure 35: Variation of different indicators of conservative/innovative scenarios <u>with/without combined heating innovations</u> with regards to baseline scenarios.

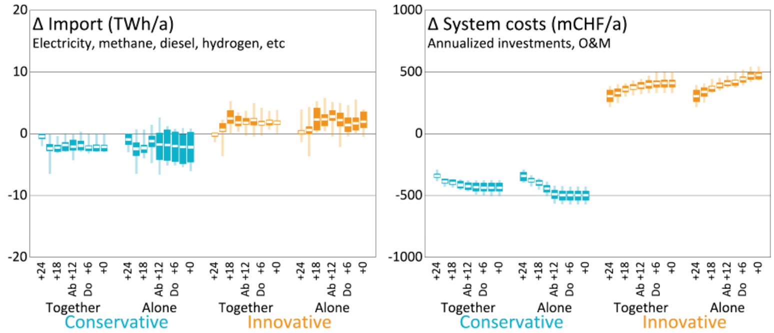


Figure 36: Variation of imports and total system costs of conservative/innovative scenarios <u>with/without low-temperature heat supply systems</u> with regards to baseline scenarios.

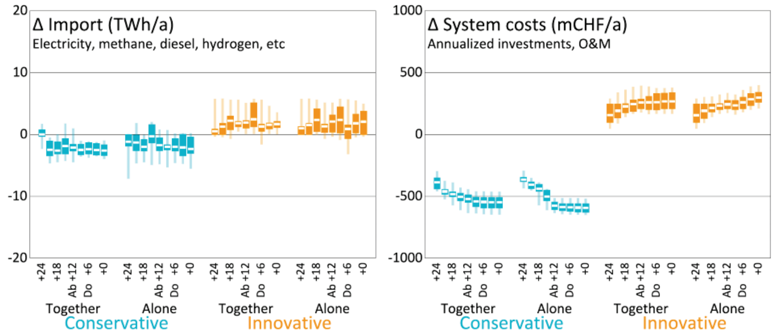


Figure 37: Variation of imports and total system costs of conservative/innovative scenarios <u>with/ without borehole regeneration & 5GDHC networks</u> with regards to baseline scenarios.

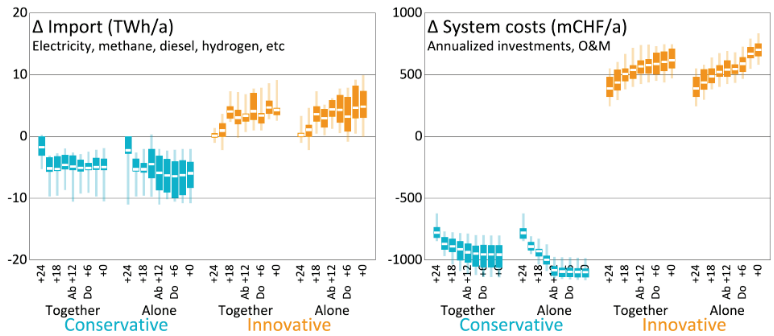


Figure 38: Variation of imports and total system costs of conservative/innovative scenarios <u>with/without combined heating innovations</u> with regards to baseline scenarios.

## 5.2 Geothermal energy

Geothermal energy has received considerable attention already in the first version of the energy strategy 2050, where an electricity generation of 4.4 TWh/a was foreseen. In absence of high enthalpy sources as they can be found in volcanic zones as Iceland, geothermal energy has to cope with the fact that temperature rises only slowly in the Swiss underground and that even at a depth of 5 km the rock temperatures will rarely exceed 150 °C. A simple estimation via a Carnot efficiency shows that electrical efficiency will not exceed 10-15 %, leading to the obvious question whether this resource should not be used directly as heat.

Four types of usage are foreseen for geothermal energy in the SES-ETH model. Starting from an assumed maximum resource of geothermal heat of 10 TWh/a, this can be used for (i) electricity generation, (ii) district heating networks, (iii) intermediate temperature process heat or (iv) medium temperature process heat. Here we assume that the energy is extracted at a depth of approx. 3 km at a temperature of 100 °C. This heat is directly used for options (i-iii) and requires an industrial heat pump with a COP of 2 to deliver medium temperature process heat at 200 °C. We characterize again the value of having or not having this resource available by *adding* it to the conservative scenarios and *removing* it from the innovative ones.

The following figures show that indeed geothermal energy is best used for intermediate and medium temperature process heat and to a smaller extent for district heating networks. The disadvantage of the latter is that the heat demand is not constant over the year, therefore the high investment costs of geothermal energy are better suited for the constant demand of industrial process heat. Figure 39 shows the results for the intermediate temperature process heat where geothermal heat can be used directly. It can be seen that adding the resource to the conservative scenarios ① reduces the contribution of CHP plants ②, direct electricity ③ and solar thermal ④ almost to zero. On the contrary, taken geothermal energy away from the innovative scenarios increases the contribution from CHPs and solar thermal. A similar behavior can be seen in Figure 41 for the medium temperature process heat where geothermal energy is supplied via a heat pump. Finally, Figure 43 shows that the availability of geothermal heat in district heating networks ⑤ reduces especially the contribution of large heat pumps ⑥.

Especially Figure 39 raises however a question: the major alternative to geothermal energy in this intermediate temperature regime of 100 °C seems to be solar thermal energy. While this is without doubt technically possible, it still appears optimistic to assume that this technology sees a widespread use in Switzerland. The approx. 5 TWh/a would require some 10 $km^2$ of collector area. We therefore repeat the four baseline scenarios and the four variations (make geothermal energy available for conservative and remove it for innovative scenarios) while removing industrial solar thermal generation from the mix. The results can be seen in Figure 40, Figure 42 and Figure 44. In absence of solar thermal generation the switch between geothermal and the alternative heat source such as CHP, direct electricity or large heat pumps becomes even more pronounced.

Since a new source is introduced with geothermal energy, it is also interesting to observe how the overall energy imports of Switzerland change. Figure 45 and Figure 46 show the results for the baseline and the variants where industrial solar thermal is removed from the mix. Indeed the availability of 10 TWh/a of geothermal energy leads to reduction of imports in the order of a few TWh/a. The same figures show also the difference in total system costs, highlighting again the benefit of having geothermal energy available.

**These findings underline the importance of pushing the introduction of geothermal energy in Switzerland as it is proposed for the additional funding of SWEET-DeCarbCH.**

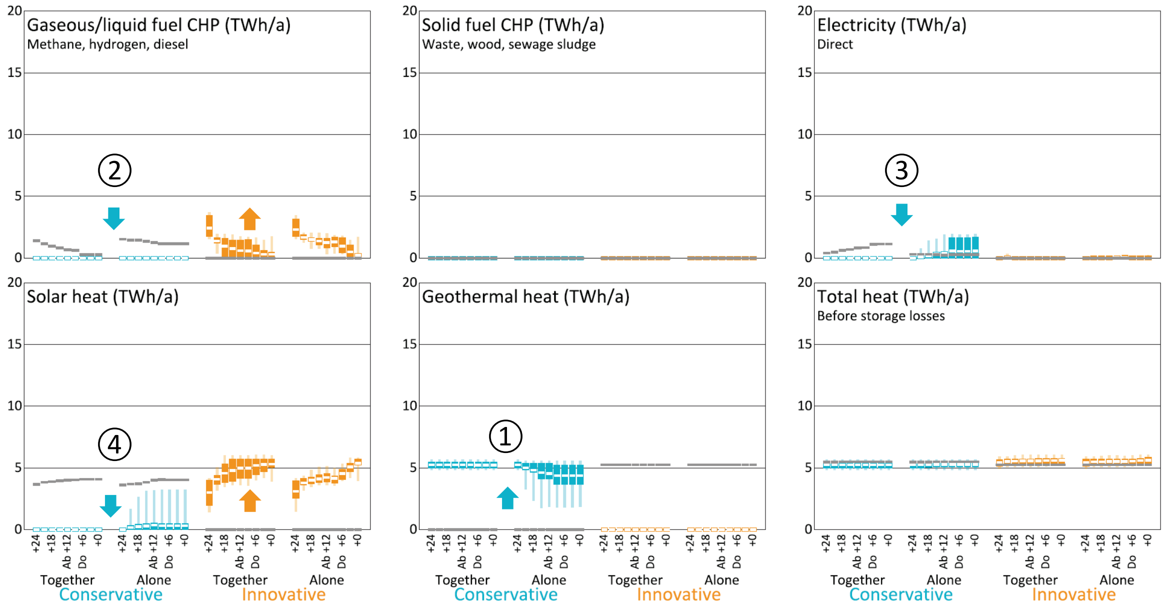


Figure 39: Intermediate temperature process heat supply for base scenarios (median shown in grey) and new scenarios with/without geothermal energy.

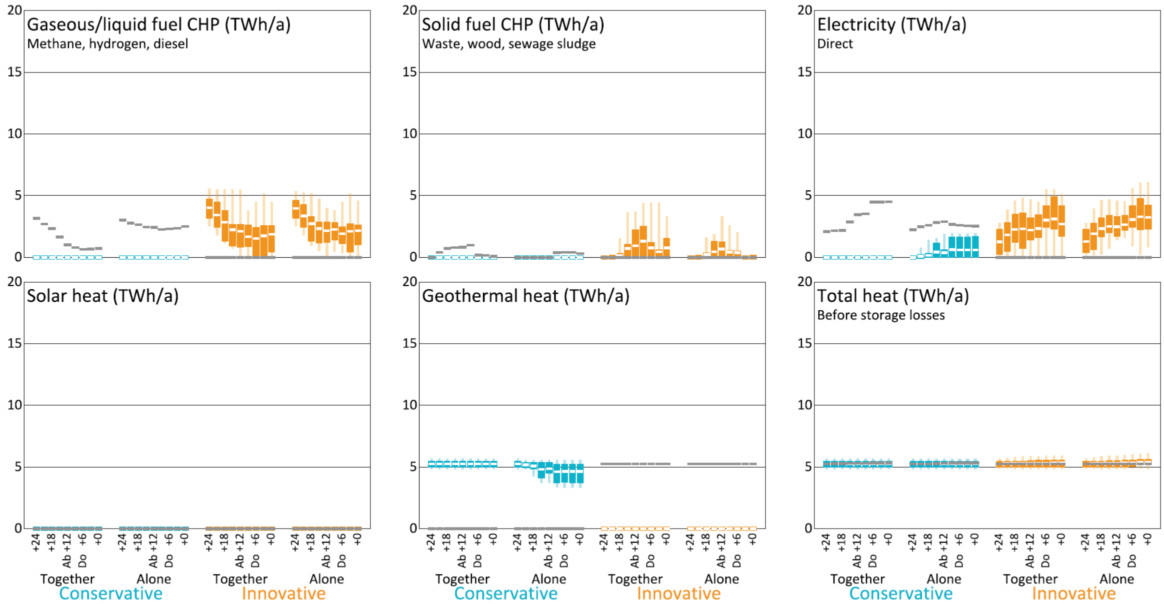


Figure 40: Intermediate temperature process heat supply for base scenarios (median shown in grey) and new scenarios with/without geothermal energy; industrial solar thermal energy is removed from the mix.

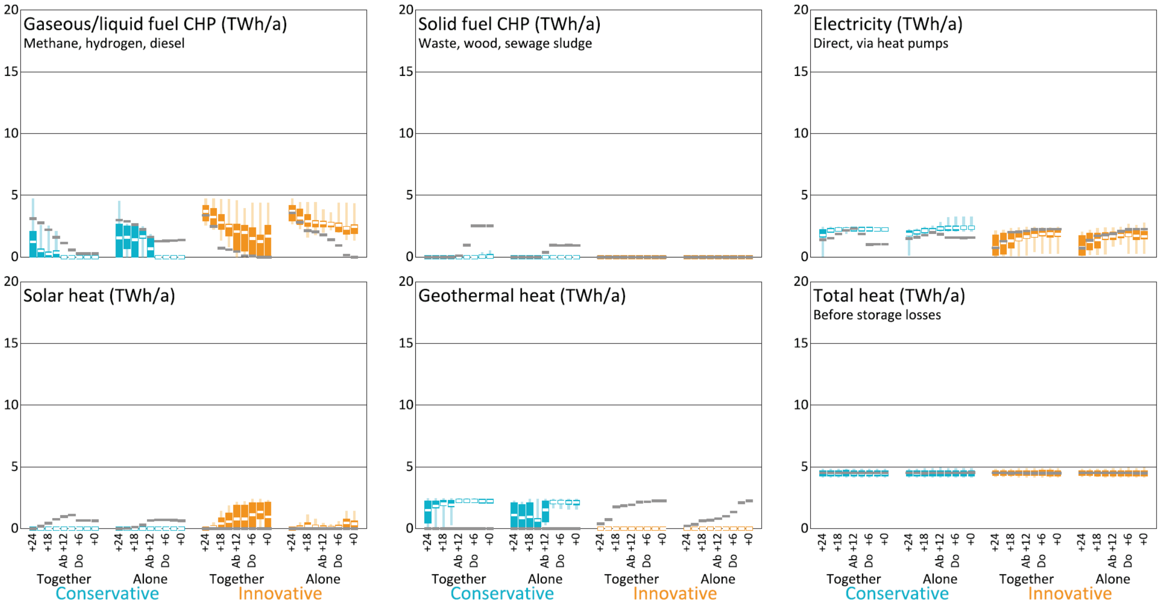


Figure 41: Medium temperature process heat supply for base scenarios (median shown in grey) and new scenarios with/without geothermal energy.

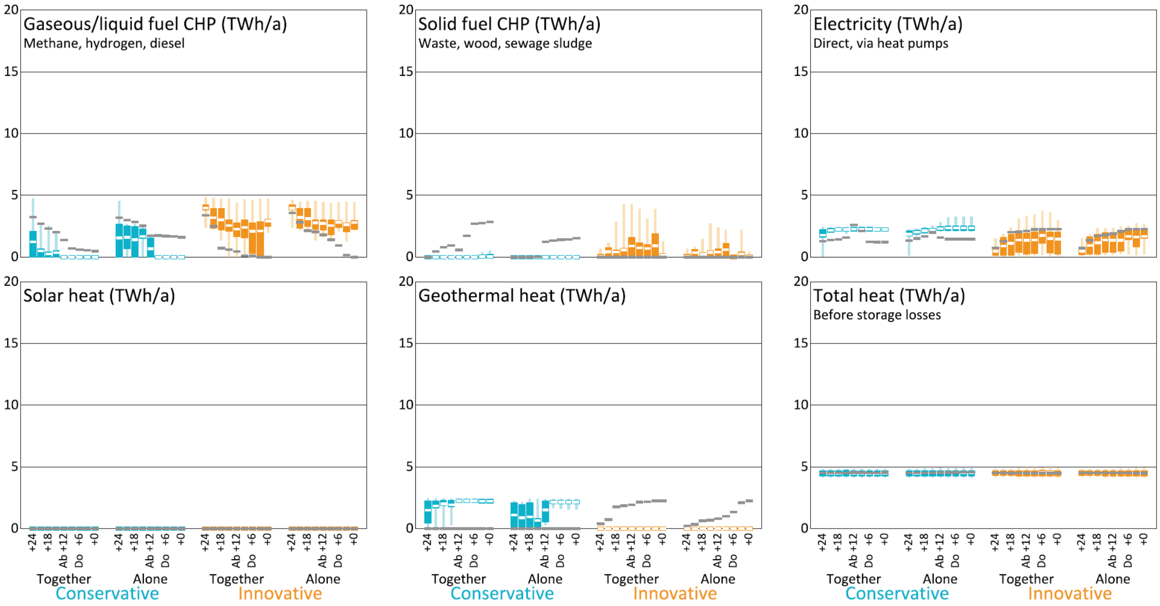


Figure 42: Medium temperature process heat supply for base scenarios (median shown in grey) and new scenarios with/without geothermal energy; industrial solar thermal energy is removed from the mix.

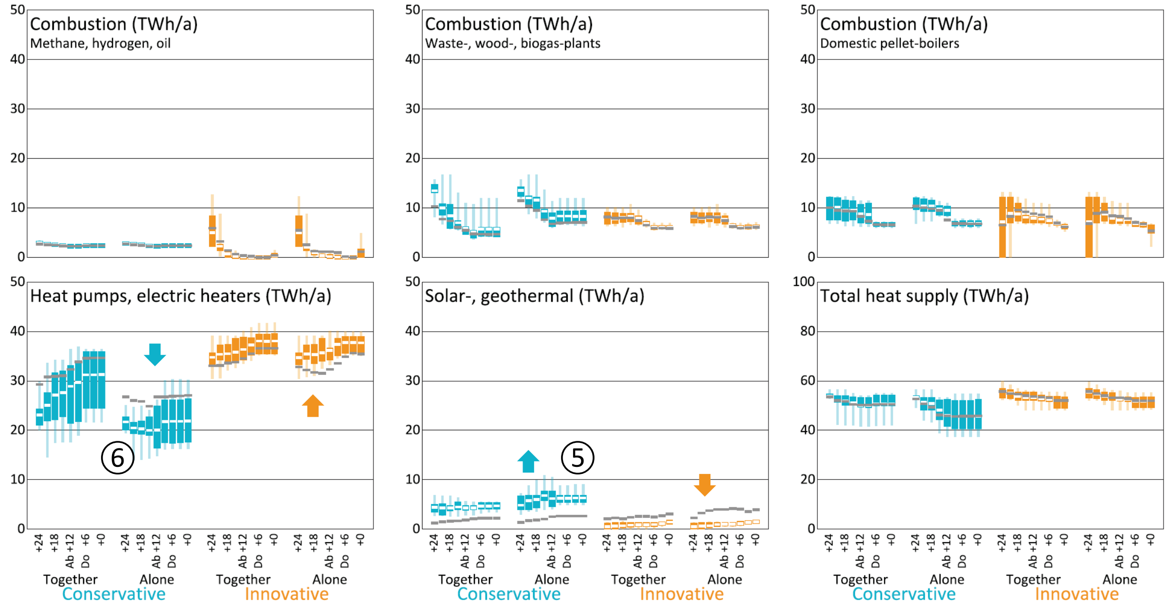


Figure 43: Space heat/DHW supply for base scenarios (median shown in grey) and new scenarios with/without geothermal energy.

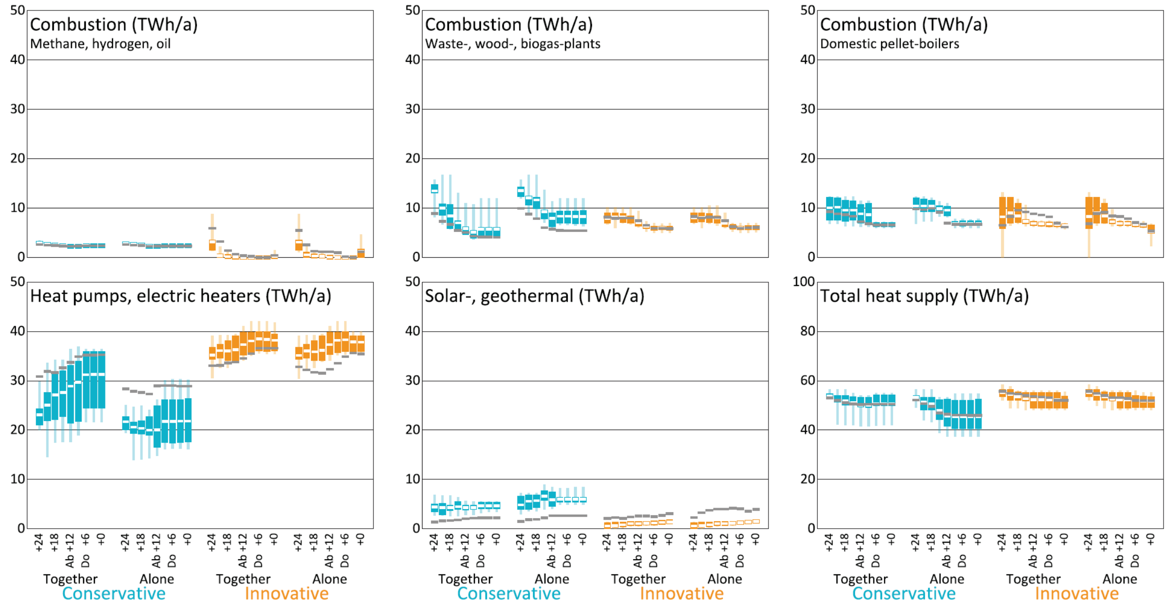


Figure 44: Space heat/DHW supply for base scenarios (median shown in grey) and new scenarios with/without geothermal energy; industrial solar thermal energy is removed from the mix.

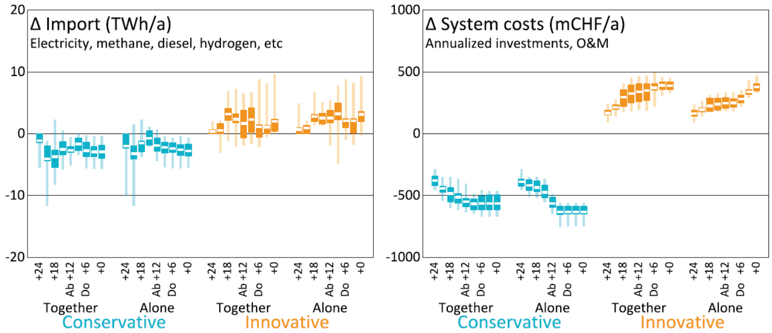


Figure 45: Variation of imports and total system costs of conservative/innovative scenarios <u>with/without geothermal energy</u> with regards to baseline scenarios.

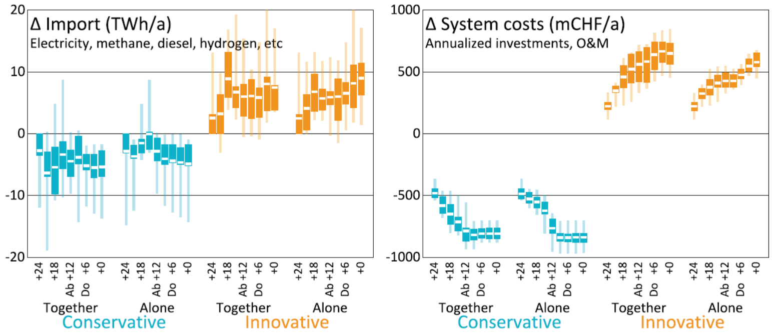


Figure 46: Variation of imports and total system costs of conservative/innovative scenarios <u>with/without geothermal energy</u> with regards to baseline scenarios; <u>industrial solar thermal energy is removed from the mix</u>.

## 5.3 Anaerobic digestion of biomass

Past research with the SCCER-Biosweet showed the importance of optimally using all available biomass resources. Here, especially the use of manure from agriculture has the potential to be increased significantly. Other types of wet biomass include sewage sludge from waste water treatment plants and green waste. The common feature of these resources is that they are best used as substrate to anaerobic digestion (AD) plants. Such plants produce biogas a mixture of roughly half methane and CO2. What happens with the biogas and the remainder of the process, the so-called digestate, has a large impact on the overall value of anaerobic digestion on a future net-zero energy system.

In this section we consider an *ideal* biogas plant – roughly modelled on the plant in Nesselnbach AG (see Figure 47). It features an anaerobic digestion process that produces biogas and digestate. Biogas is assumed to consist of 54% methane and 46% CO2. Two options exist as a next step, either the combustion in a combined heat & power (CHP) plant – normally a reciprocating engine – that delivers electricity and heat, or a biogas upgrade that separates bio-methane from CO2 using a membrane process. In the latter case, the separated CO2 is liquefied and made available either for storage or use. The digestate undergoes a separation into a liquid fraction that is used as fertilizer and a solid fraction that can be either combusted in industrial burners or CHP plants, or be used as a feedstock for hydrothermal gasification, liquefaction or carbonization (HTX). Note that the plant in Nesselnbach has all aforementioned features except the hydrothermal processing of the digestate which is instead sold to the cement plant in Wildegg-Brugg.

In contrast to this *ideal* anaerobic digestion plant, a typical *real* plant as it is used today has only the anaerobic digestion and a CHP engine, and the digestate is used as fertilizer on the fields. Here we assume that the CO2 contained in the latter will eventually be released back to the atmosphere. As explained in Section 3, the innovative/conservative scenarios have the ideal/real AD plant, respectively. In order to see the value of such an ideal AD plant we analyze variants to the base scenarios where elements of the ideal plant are added to the conservative and removed from the innovative scenarios.

Figure 48 shows the usage of biogas and digestate in the base scenarios. In the conservative cases, biogas can only be used for direct combustion in a CHP plant ① and digestate is not available for the energy system. In the innovative cases there is a transition from the local usage of biogas in small CHP plants to the upgrading to bio-methane ② that is fed to the gas grid and therefore made available for other types of plants which are more efficient and allow for CO2 separation and storage (generating also negative emissions). The digestate is completely used for hydrothermal processes ③, mostly to produce a liquid fuel. The advantages of the innovative scenario is obvious: one resource – biogas – is made available to other users and can also be stored for winter power & heat generation, the other resource – digestate – is converted to another valuable energy carrier.

The first experiment is the remove the availability of biogas upgrading and hydrothermal processes from the innovative scenarios and make it available to the conservative ones. Figure 49 shows that the picture is simply flipped compared to Figure 48, i.e. biogas is upgraded and digestate is used for HTX for the conservative scenarios. As explained before, those two options increase the availability of locally sourced energy resources, therefore one can expect a benefit on the overall primary energy imports. Indeed, Figure 50 shows that the imports of methane decline by some 5-10 TWh/a for the conservative scenarios and increase by 5-10 TWh/a for the innovative ones ④. There is an additional effect that can be seen in Figure 51, namely the provision of CO2 that can be easily separated during the biogas upgrading and the hydrothermal processes ⑤. This reduces the need to separate CO2 from other processes, such as waste to energy plants ⑥ and most importantly direct air capture ⑦.

As a next step, we repeated this analysis for the two innovations separately. When biogas upgrading is not available, Figure 52 shows a similar trend as before, namely a reduction of primary energy imports, mostly methane. Figure 53 shows the effect of CO2 separation where now only the biogas upgrading contributes, therefore the effect of reducing direct air capture is smaller. A similar trend can be seen in Figure 54 and Figure 55 when the HTX technologies are made available to the Conservative scenarios and removed from the Innovative ones.

The last modification concerns the option to use the digestate directly as a solid fuel for power and heat generation. This is currently done in Nesselnbach, however, it is not clear whether this will be possible in the future. At least digestate from water purification plants will have to be processed for phosphate recovery and also the residues of other anaerobic digestion facilities contain valuable nutrients which cannot be recovered when the digestate is burned in a furnace. Nevertheless, Figure 56 shows that such a solid fuel will be used for generating high temperature process heat in industry ⑧. It reduces the need for methane and electricity ⑨. Figure 57 shows the same trend, namely a reduction of methane use for heat generation ⑩. In the innovative scenarios this methane is used for mobility purposes ⑪, in the conservative ones the overall consumption is reduced ⑫.

Figure 58 shows again the positive effect on CO2 separation. Having digestate available as an additional solid fuel increases the possibility to capture CO2 from industrial installations and waste-to-energy plants, reducing the need for direct air capture. It is important to point out that this effect is only visible for the conservative scenarios. In the innovative scenarios, digestate is used for hydrothermal processes that also allow for CO2 capture. Finally, Figure 59 to Figure 62 illustrates the overall effect of innovations in the field of anaerobic digestion plants on imports and total system costs.

Figure 63 illustrates the annual time series for several of the aforementioned variants. Starting from the top row it can be seen that all wet biomass is converted into biogas and digestate. Then the digestate is either lost to the energy system or undergoes hydrothermal conversion to liquid fuels or methane. Alternatively, it is burned to produce high temperature process heat. The fifth and sixth rows shows the use of biogas for upgrading to methane and combustion in a CHP plant, respectively. The latter delivers electricity and low grade heat. This heat is used to satisfy the need for space heat, however, a large part cannot be used in summer and is lost. The last rows summarizes all conversion steps by showing how much of the original energy content of the wet biomass is actually turned into a useful energy service. Clearly, the most simple approach of local anaerobic digestion with CHP is inferior to all other options.

The results presented in this section highlight the importance of a proper use of wet biomass. Using the resource locally to generate biogas to produce heat and power is sub-optimal since the heat can generally not be properly utilized, electricity is produced also in summer when it has a low value and the opportunity to generate negative CO2 emissions is missed. An upgrading of biogas to bio-methane that is fed to the gas grid and CO2 that can be stored is essential. Note that an upgrading of CO2 with hydrogen from electrolysis to synthetic methane never appears in our results. The next important decision is the use of the digestate, i.e. the residues of the anaerobic digestion process. Here the model suggests that the use of digestate as a fuel to generate process heat would be the optimal solution. This may however be in contradiction to the need for nutrient recovery (phosphorus, nitrogen, salts, etc), which may be realized better using a hydrothermal processing of the digestate. Whenever this group of technologies is made available to the system, it is taken to produce either methane or a liquid fuel that can both be stored and used for high temperature heat or electricity generation.

**All these additions to the simple anaerobic digestion plant with a gas motor require quasi-industrial installations which can hardly be realized on the typical small Swiss farm. Therefore a centralization with a few dozens of facilities that are properly connected to the gas grid is highly beneficial.**

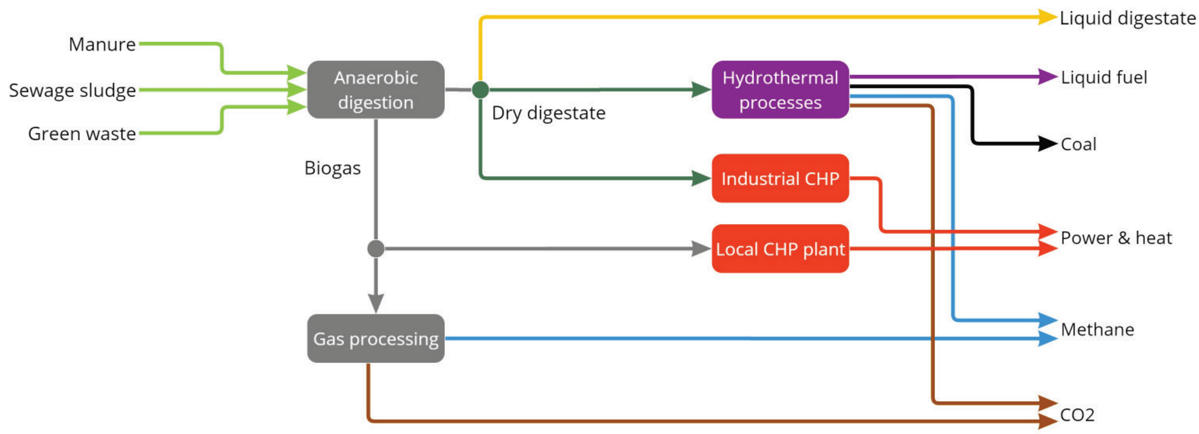


Figure 47: Simple representation of biogas facility.

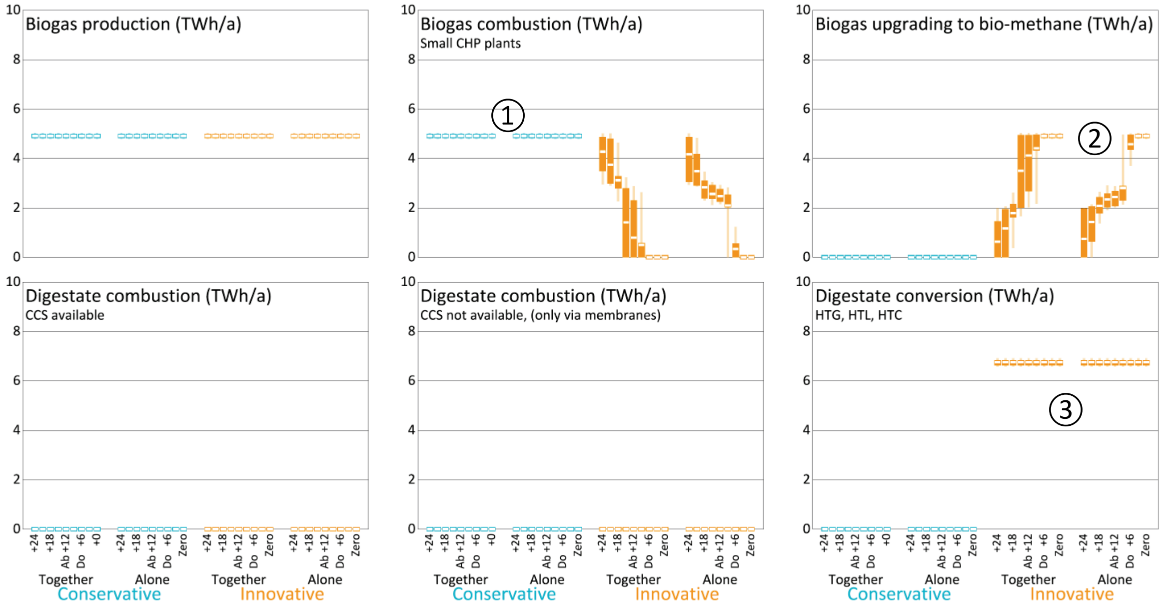


Figure 48: Usage of biogas and digestate in the base scenarios.

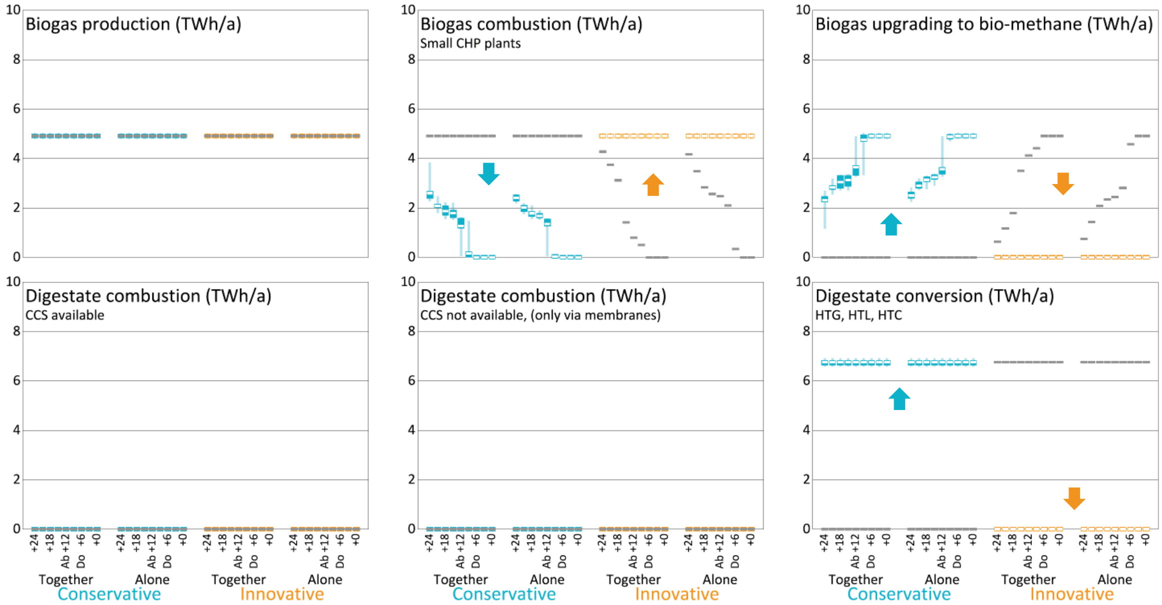


Figure 49: Usage of biogas and digestate for base scenarios (median shown in grey) and new scenarios <u>with/without biogas upgrading to methane/CO2 and HTX</u>.

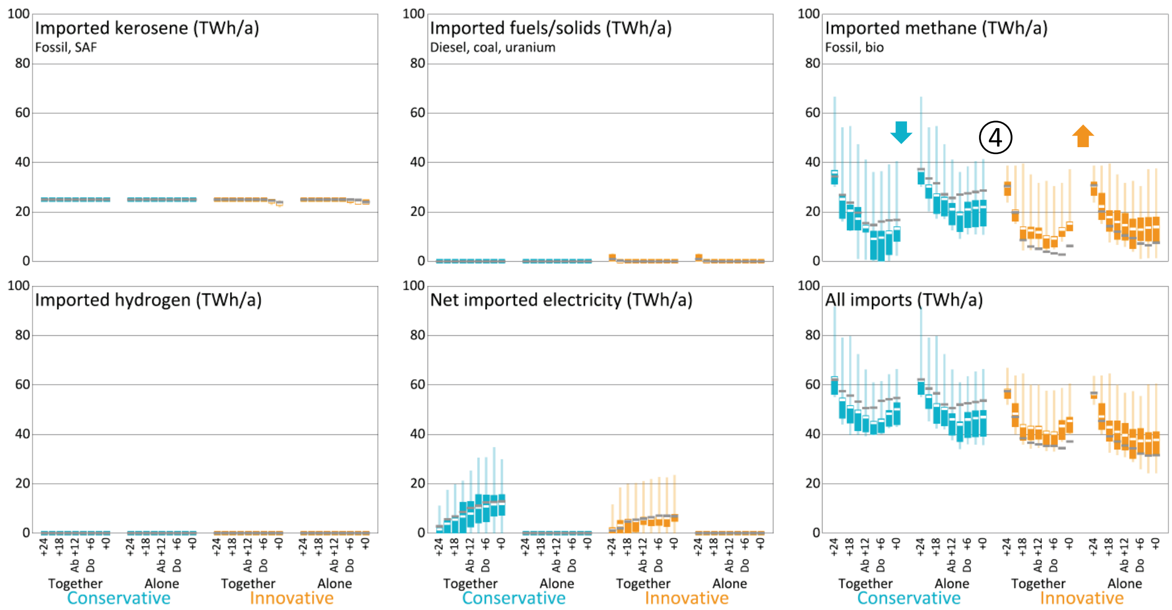


Figure 50: Primary energy imports for base scenarios (median shown in grey) and new scenarios <u>with/without biogas upgrading to methane/CO2 and HTX</u>.

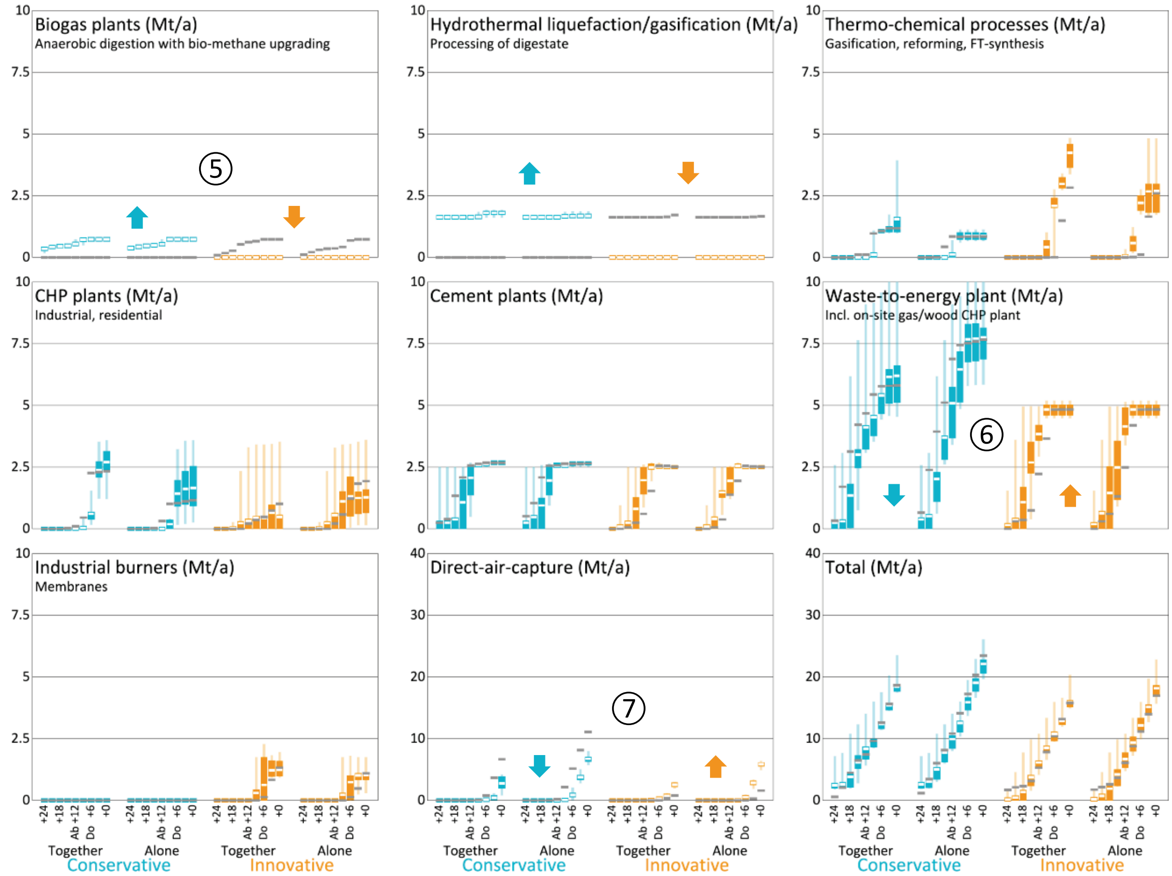


Figure 51: CO2 separation for base scenarios (median shown in grey) and new scenarios <u>with/without biogas upgrading to methane/CO2 and HTX</u>.

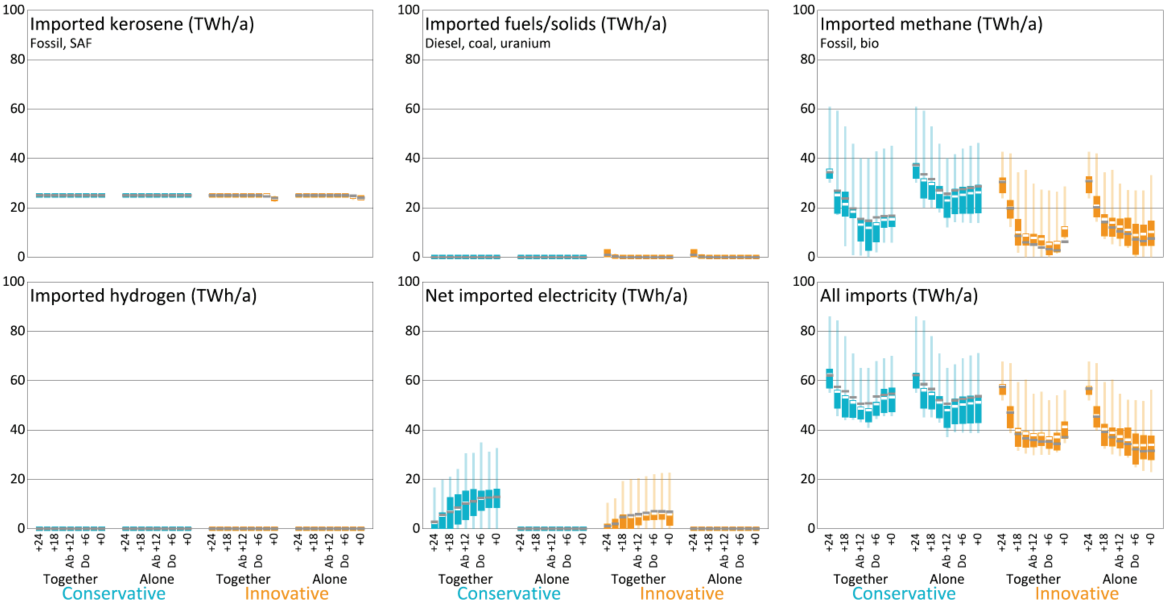


Figure 52: Primary energy imports for base scenarios (median shown in grey) and new scenarios with/without biogas upgrading to methane/CO2.

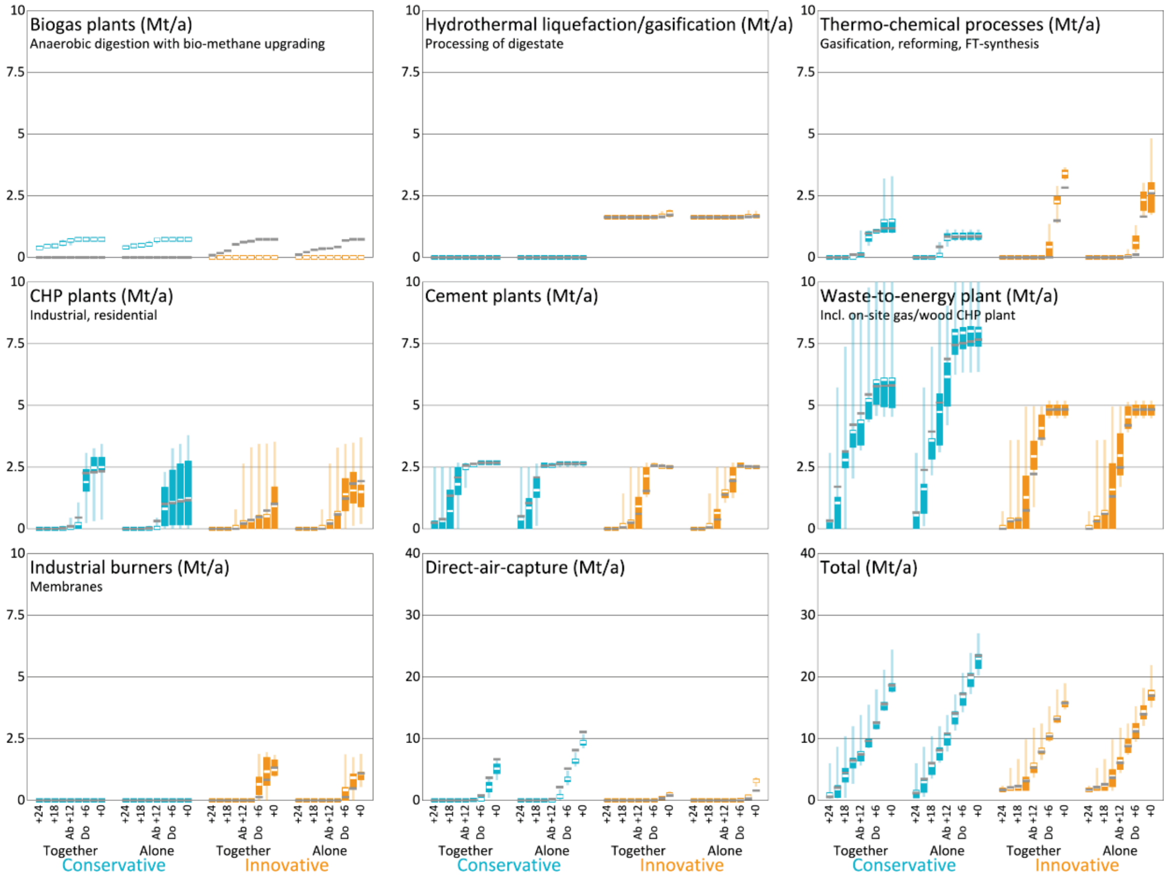


Figure 53: CO2 separation for base scenarios (median shown in grey) and new scenarios with/without biogas upgrading to methane/CO2.

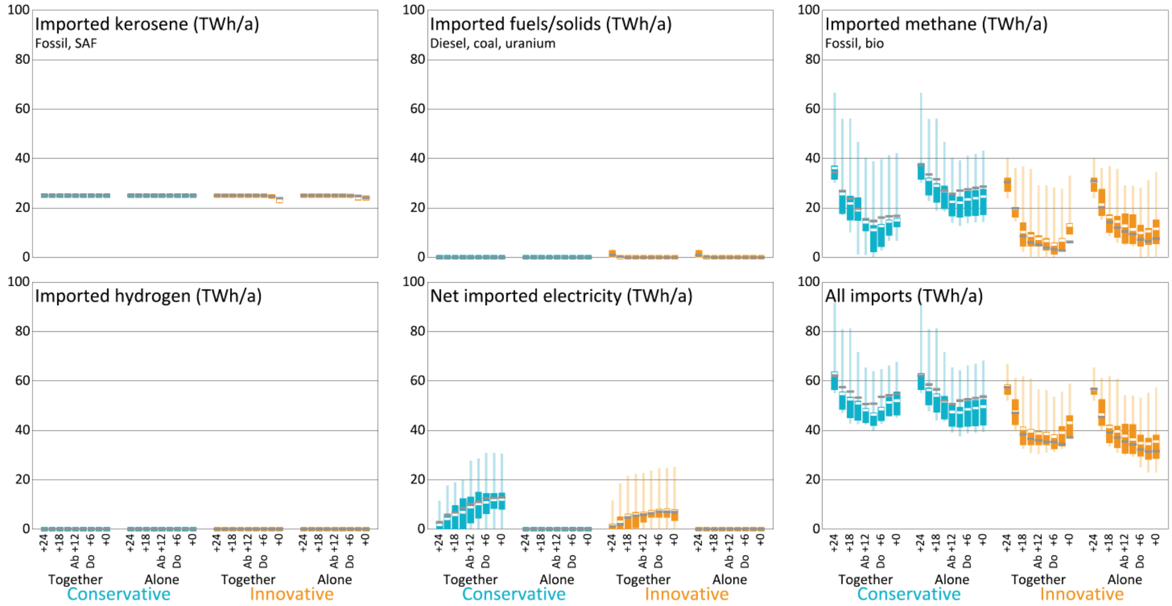


Figure 54: Primary energy imports for base scenarios (median shown in grey) and new scenarios with/without HTX.

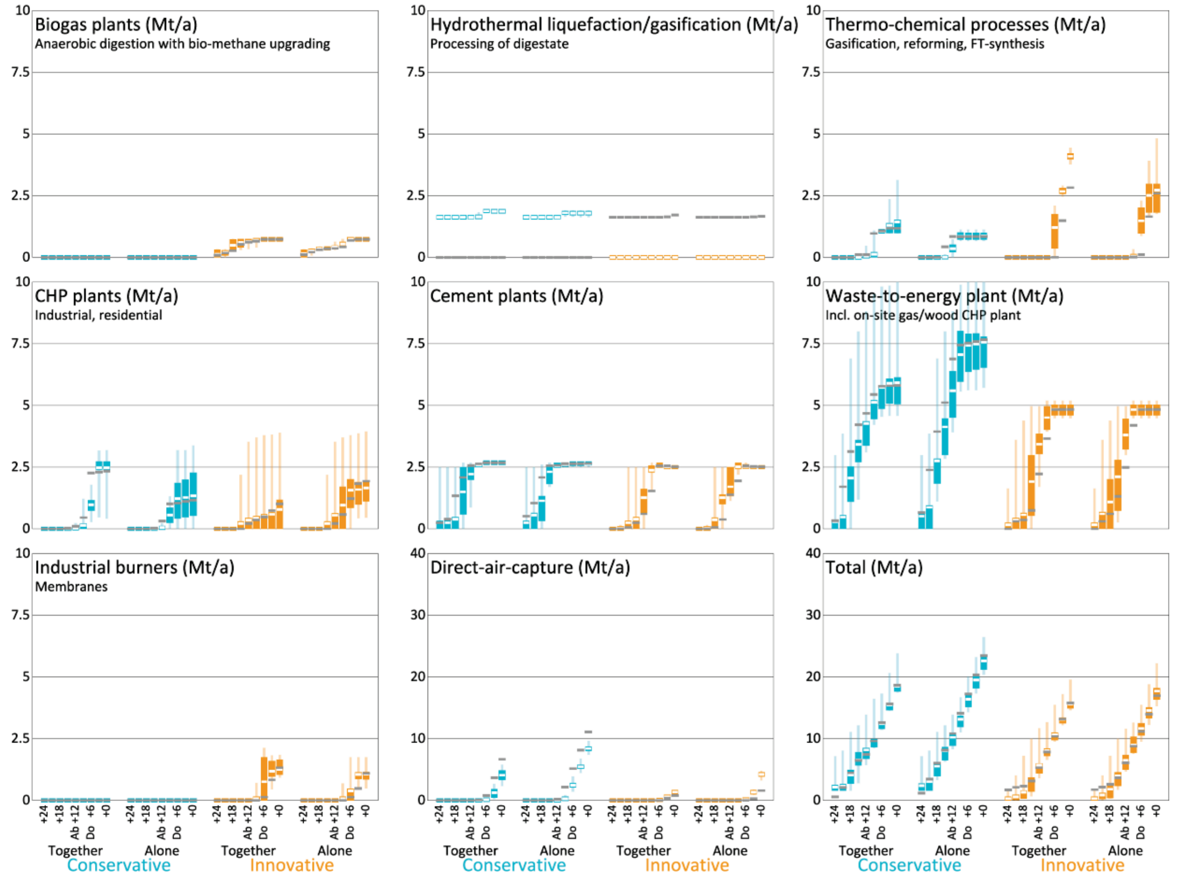


Figure 55: $CO_2$ separation for base scenarios (median shown in grey) and new scenarios with/without HTX.

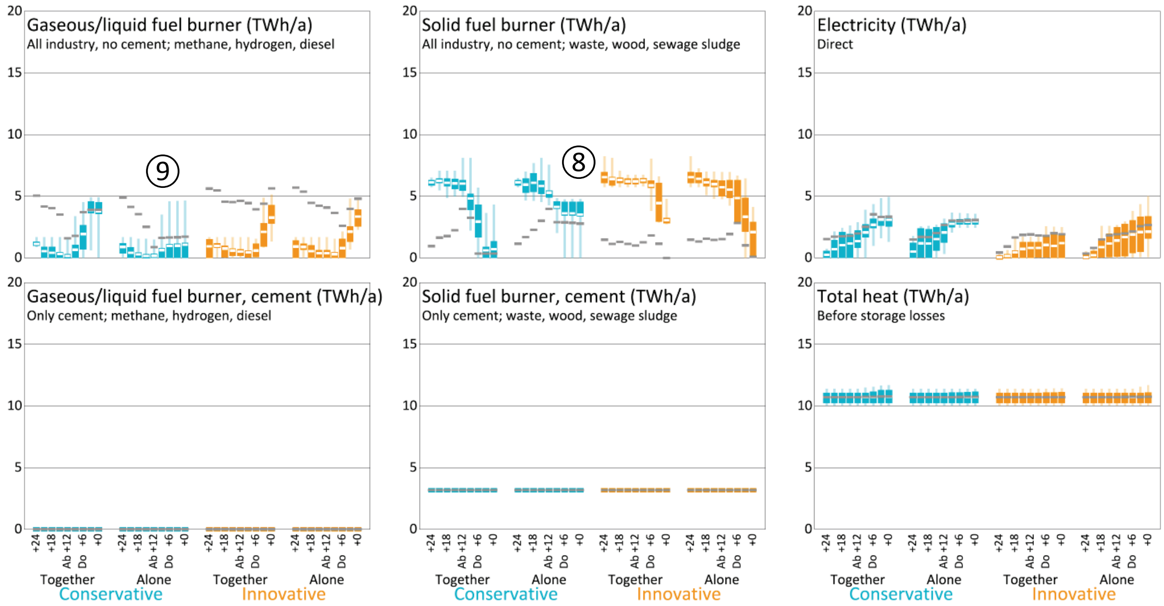


Figure 56: Supply of high temperature process heat for base scenarios (median shown in grey) and new scenarios <u>with the option to use digestate as solid fuel</u>.

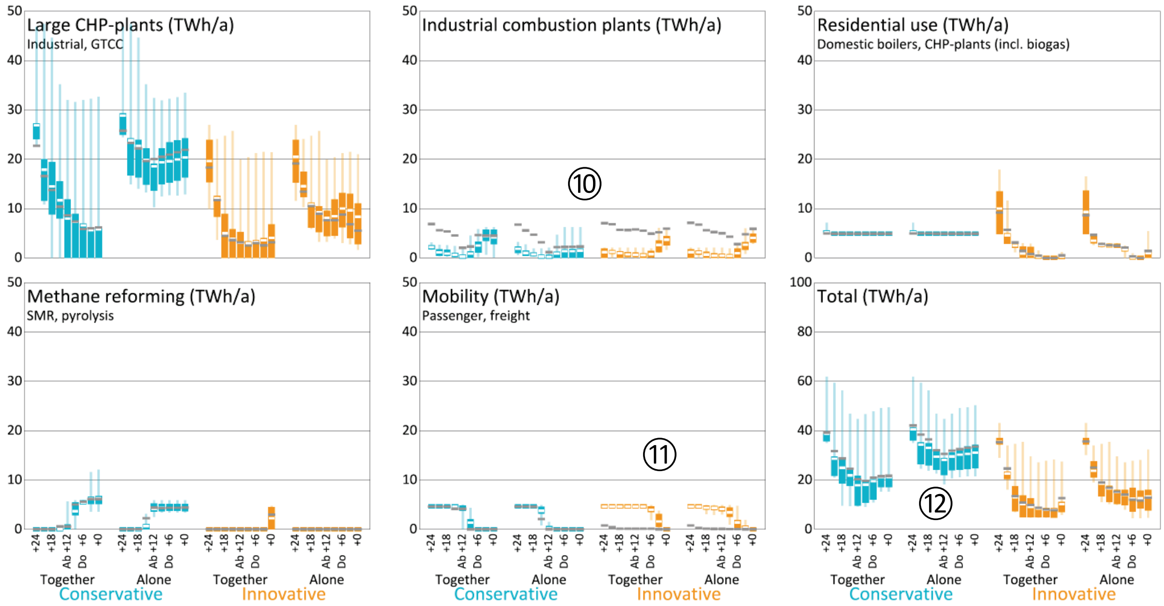


Figure 57: Use of methane for base scenarios (median shown in grey) and new scenarios <u>with the option to use digestate as solid fuel</u>.

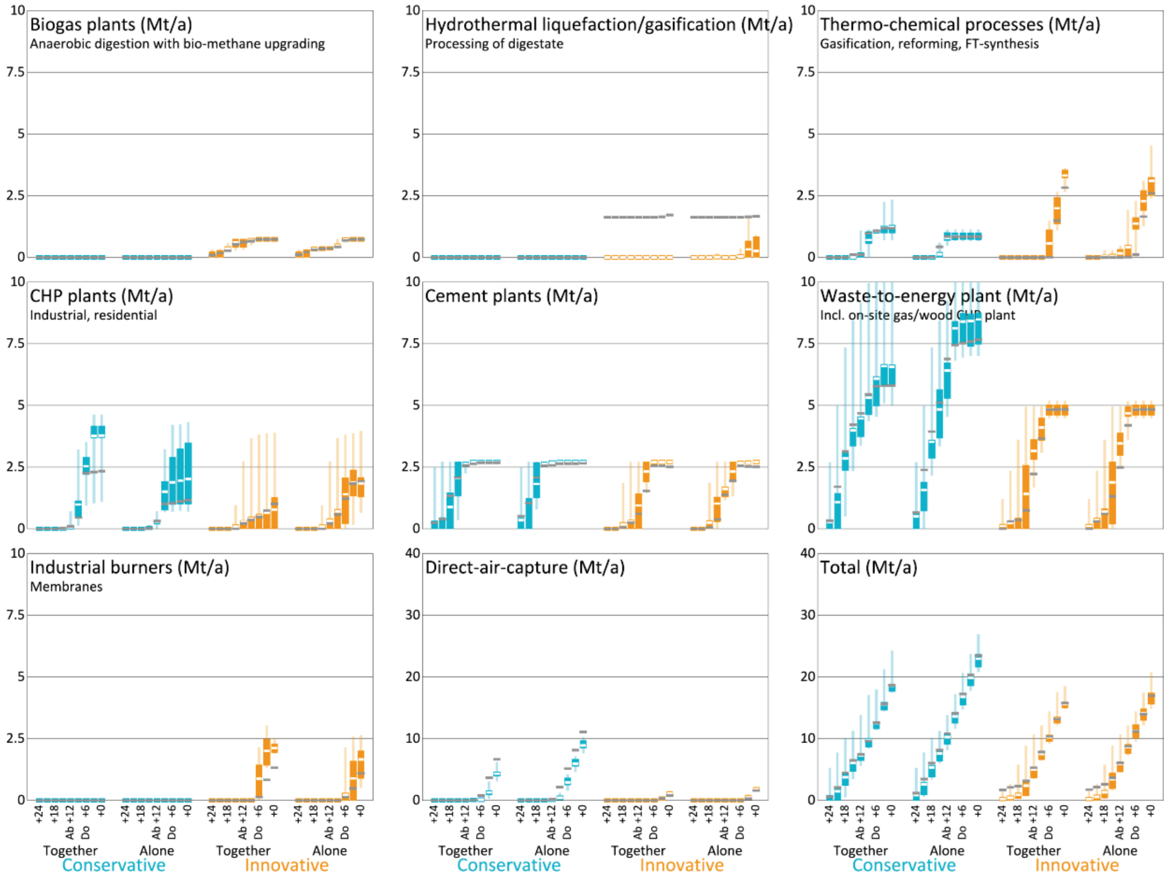


Figure 58: CO2 separation for base scenarios (median shown in grey) and new scenarios <u>with the option to use digestate as solid fuel</u>.

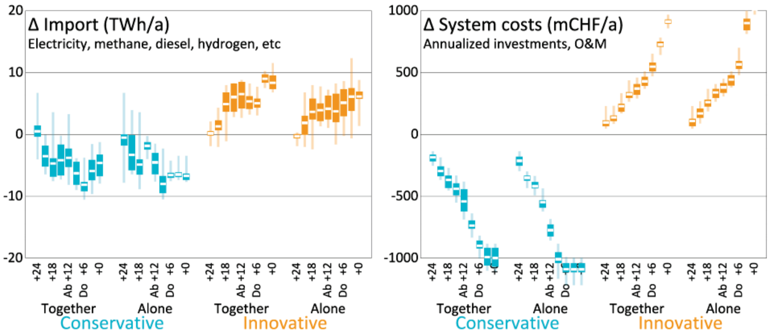


Figure 59: Variation of imports and total system costs of conservative/innovative scenarios <u>with/without biogas upgrading to methane/CO2 and HTX</u> with regards to baseline scenarios.

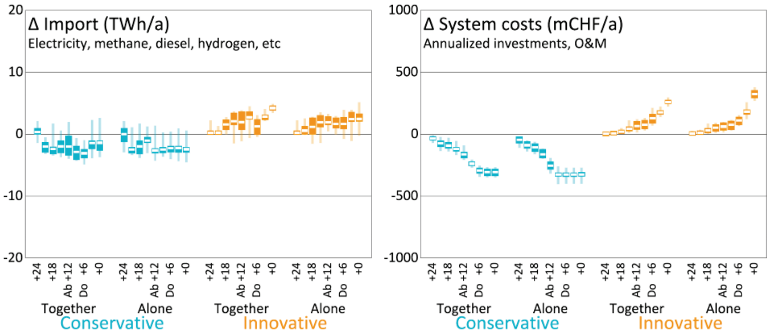


Figure 60: Variation of imports and total system costs of conservative/innovative scenarios <u>with/without biogas upgrading to methane and CO2</u> with regards to baseline scenarios.

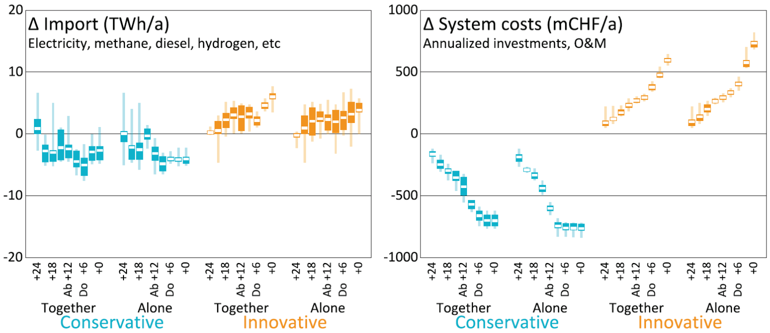


Figure 61: Variation of imports and total system costs of conservative/innovative scenarios <u>with/without HTX</u> with regards to baseline scenarios.

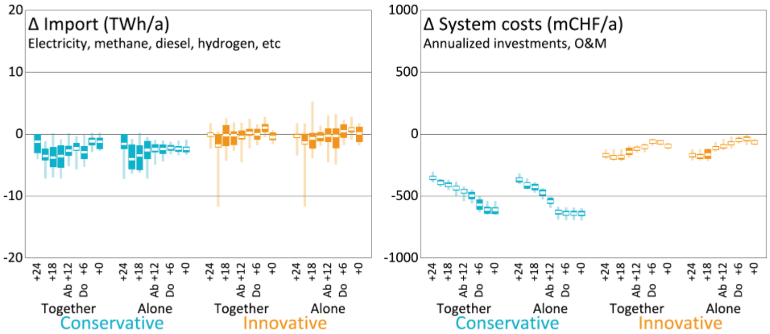


Figure 62: Variation of imports and total system costs of conservative/innovative scenarios <u>with the option to use digestate as solid fuel</u> with regards to baseline scenarios.

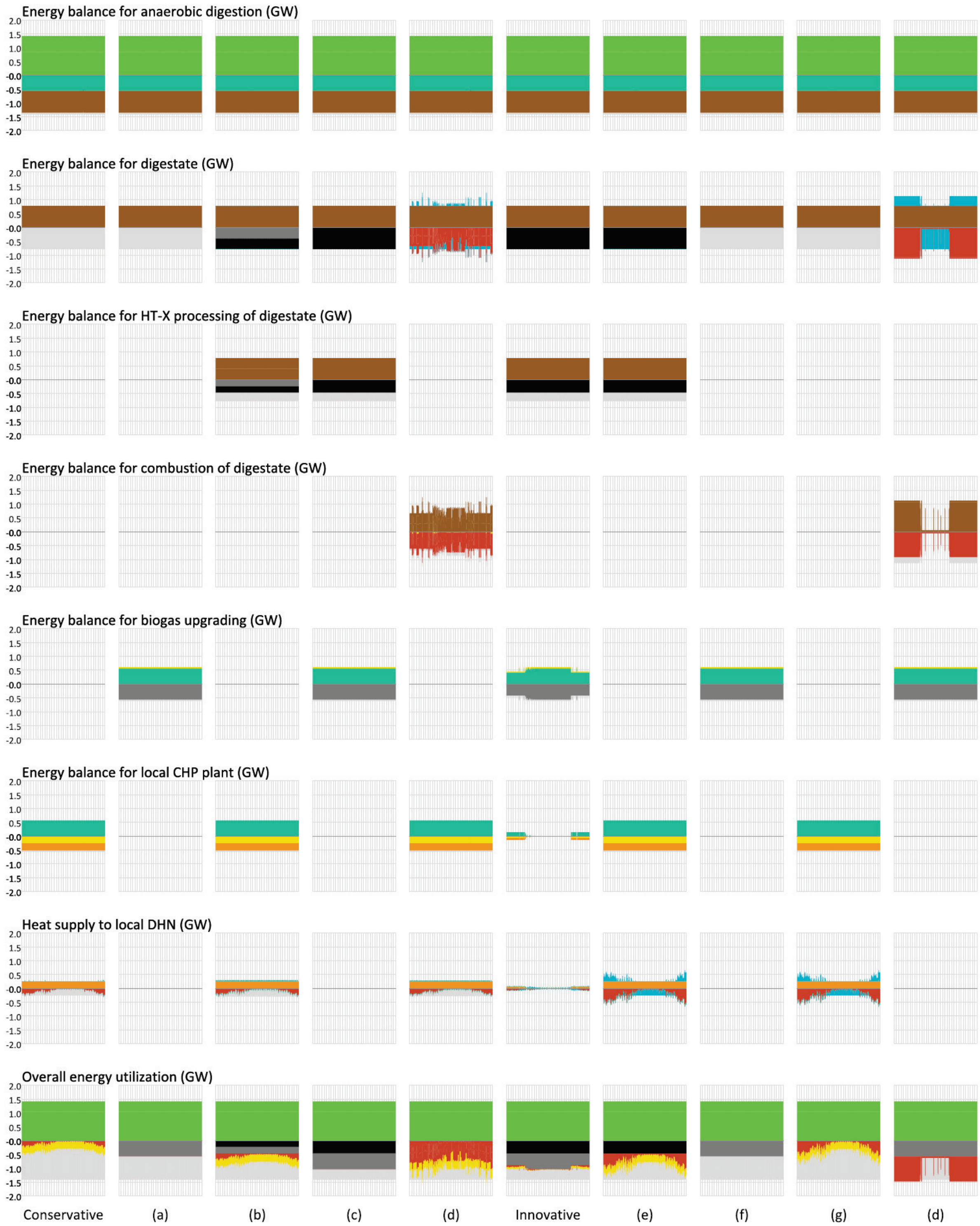


Figure 63: Annual time series for wet biomass processing for different variants, typical Alone scenario at 6 $Mt_{CO2}$/a (Domestic): (a) with biogas upgrading, (b) with HTX technologies, (c) with biogas upgrading and HTC technologies, (d) with digestate combustion, (e) without biogas upgrading, (f) without HTX technologies, (g) without biogas upgrading and HTX technologies; wet biomass ■, biogas ■, digestate ■, methane ■, liquid fuels ■, electricity ■, low grade heat ■, process heat ■, losses ■.

## 5.4 Membranes for $CO_2$ separation

The largest point sources of $CO_2$ in Switzerland are the 6 cement plants (500-1000 kt/a) and the 29 waste-to-energy plants (100-300 kt/a). Smaller sources are wood combined heat and power plants that deliver heat to industry or district heating networks (50-100 kt/a). All other emitters are smaller from a large boiler that serves industry or a heating network (5-20 kt/a) down to a residential oil or gas heating (few t/a).

$CO_2$ separation from large point sources is best achieved with absorption based technologies like amine scrubbing. This may not be suited for smaller combustion systems of a few kt/a that are found in industry or small district heating networks (see examples in Figure 64). Here membranes can be an alternative, as they are commercialized by the ETH spin-off UniSieve. As described in Section 3, we assigned this option to the innovative scenarios, not to the conservative ones. It is applied to industrial combustion of gases/liquids (archetype HTH1, see Section 2.2) and solid fuels (HTH2), and to gaseous/liquid und solid fuel fired CHP units that deliver process steam (MTH1, MTH2, ITH1, ITH2). We characterize the value of having or not having this technology available by *adding* it to the conservative scenarios and *removing* it from the innovative ones.

The addition of membranes to the mix has a number of consequences: Figure 65 shows that in the conservative scenario wood is used to some extent in residential and industrial CHP plants ① that have amine based CO2 separation as an option. When membranes become available, this wood is re-directed to industrial burners that deliver high temperature process heat ②. The same trend can be observed for the use of waste ③ ④ in Figure 66. The increased use of wood and waste for high temperature process heat ⑤ leads to a reduction of electric heating ⑥ and to a reduced use of methane for industrial high temperature process heat ⑦ (see Figure 67). This methane can now be used in CHP plants to efficiently generate more electricity ⑧, reducing also the need for photovoltaic generation ⑨ (see Figure 68). On the electricity demand side, the reduction for process heat is visible ⑩ and is only partially compensated by an increase for other processes that includes the electrical energy needed for the CO2 separation by membranes ⑪ (see Figure 69). Overall, the electricity demand decreases slightly. Finally, Figure 70 shows the CO2 separation from the various point sources. Again there is a visible shift from CHP plants ⑫ to combustion systems that use membranes ⑬. A secondary positive effect is that less direct air capture is needed ⑭ since more negative emissions are being generated.

This whole chain of shifts is much less pronounced for the innovative scenario. This can be understood from the end of the chain since much less gas power generation is needed for the innovative scenarios, meaning that the use of membranes that eventually frees up methane for power generation is less valuable. Finally, Figure 71 shows the impact on overall imports and total system costs which is much more pronounced in the conservative scenarios due to the reasons mentioned before.

**In summary, having membranes available for CO2 separation from smaller industrial emitters appears to have a positive effect on the energy system.**

Figure 64: Examples of medium size combustion systems: Heizzentrale Dättwil (left), Heizzentrale Hönggar Berg ETH (right).

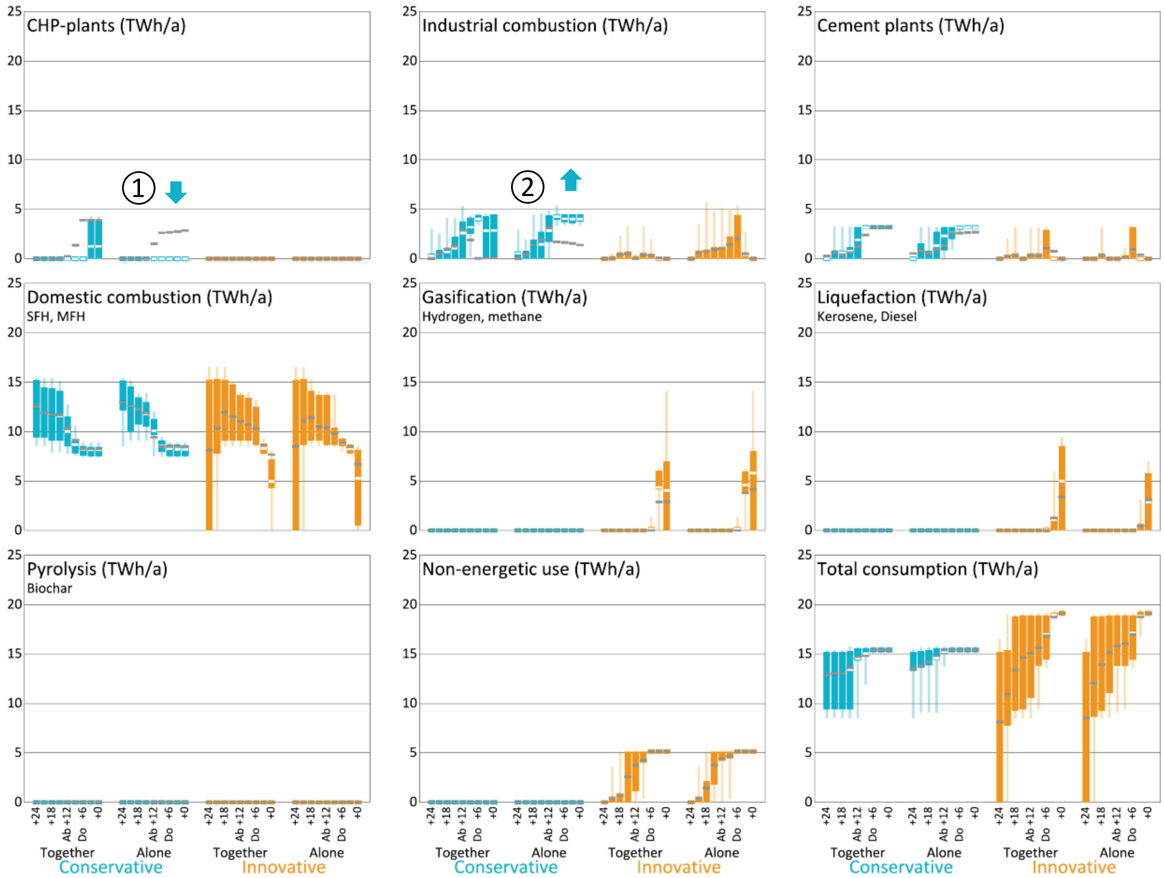


Figure 65: Usage of wood for base scenarios (median shown in grey) and new scenarios with/without membranes for CO2 separation.

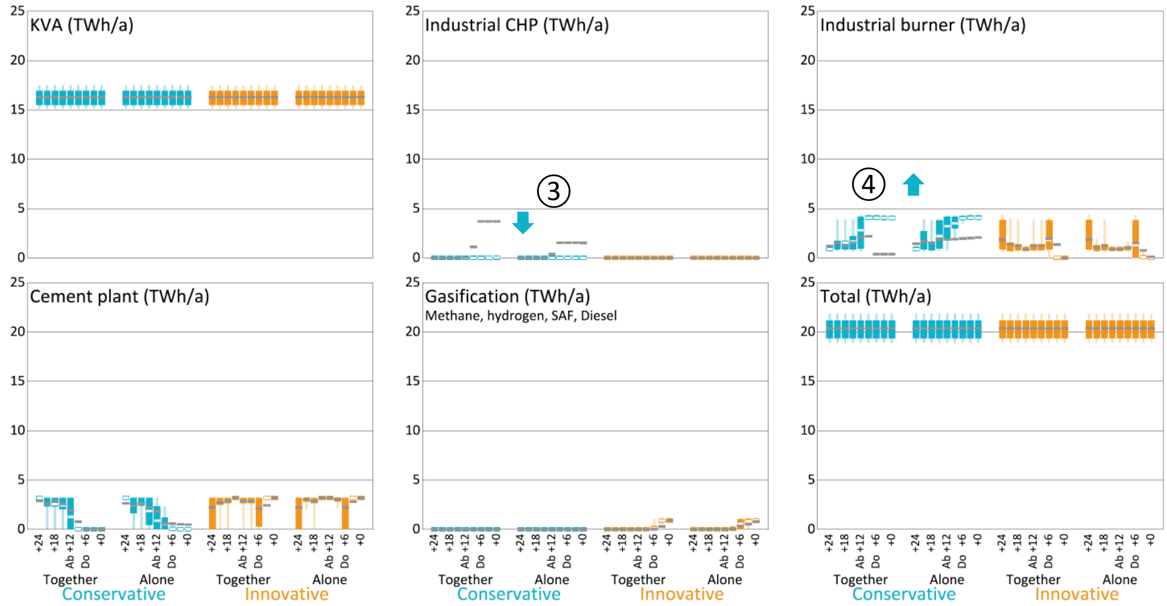


Figure 66: Usage of waste for base scenarios (median shown in grey) and new scenarios with/without membranes for CO2 separation.

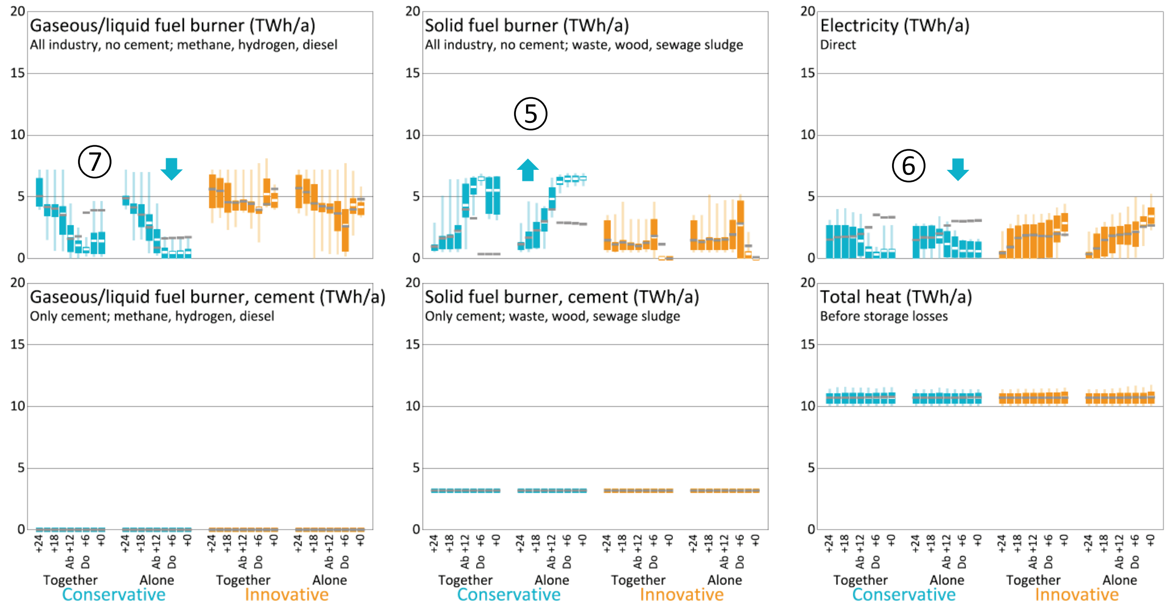


Figure 67: High temperature process heat supply for base scenarios (median shown in grey) and new scenarios with/without membranes for CO2 separation.

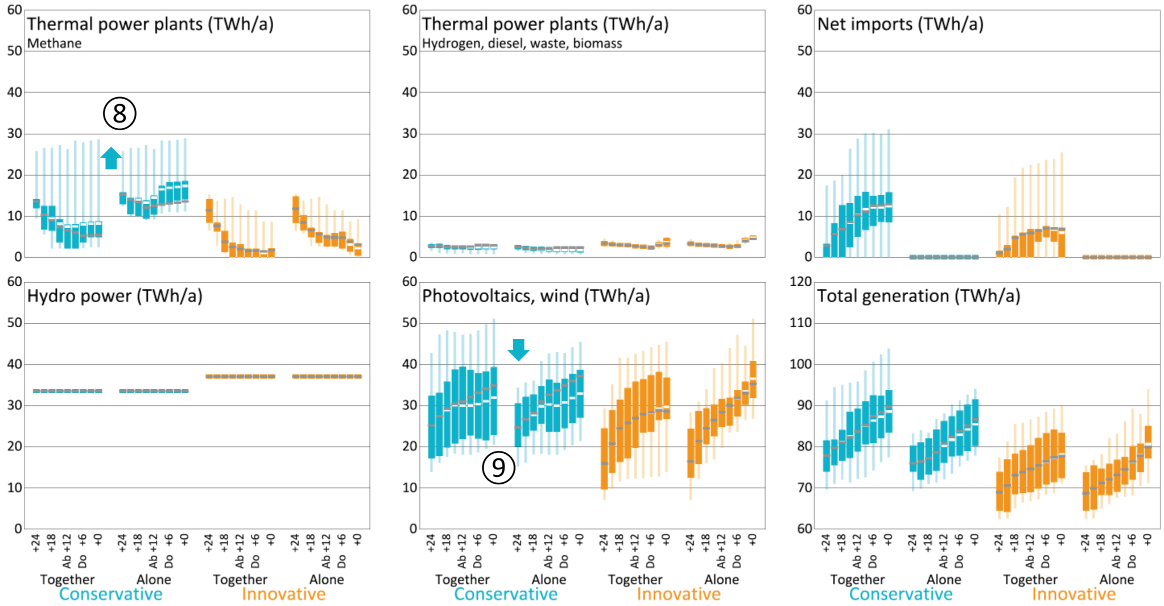


Figure 68: Electricity generation for base scenarios (median shown in grey) and new scenarios with/without membranes for CO2 separation.

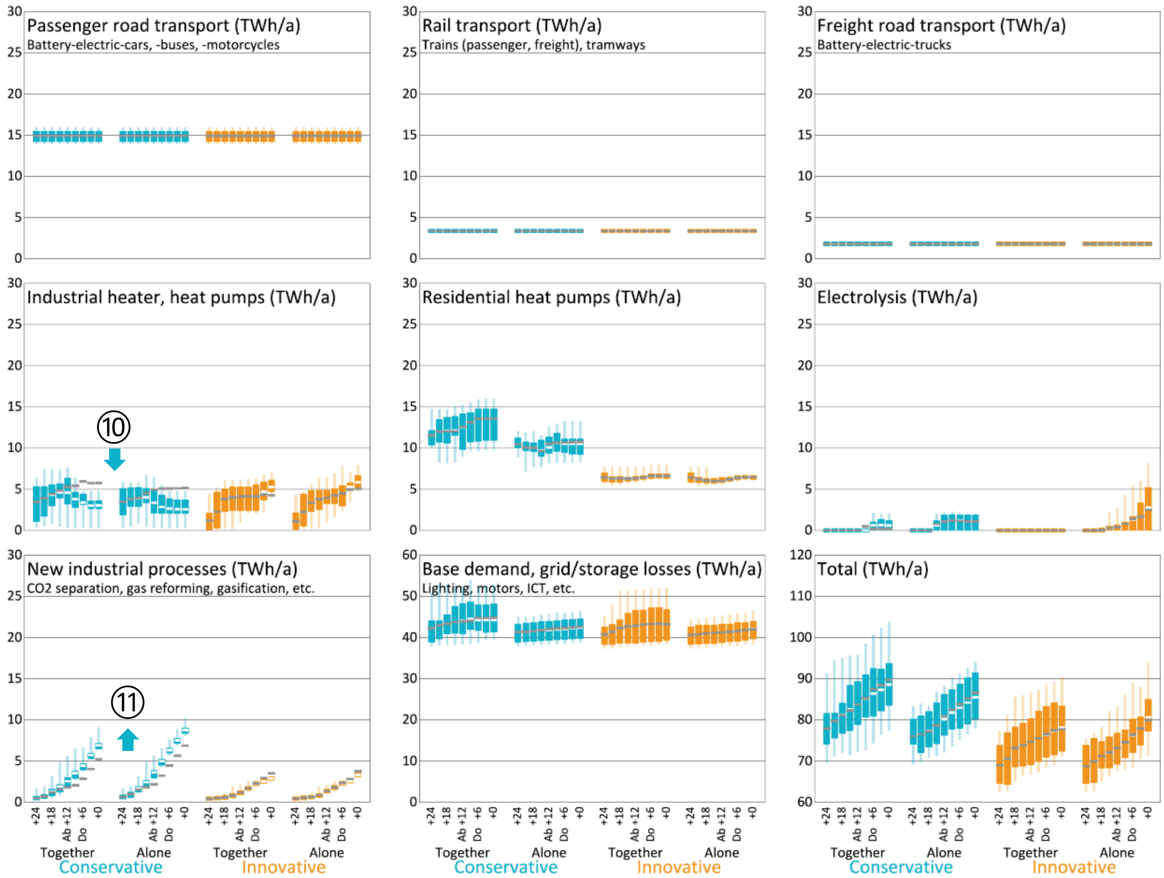


Figure 69: Electricity consumption for base scenarios (median shown in grey) and new scenarios with/without membranes for CO2 separation.

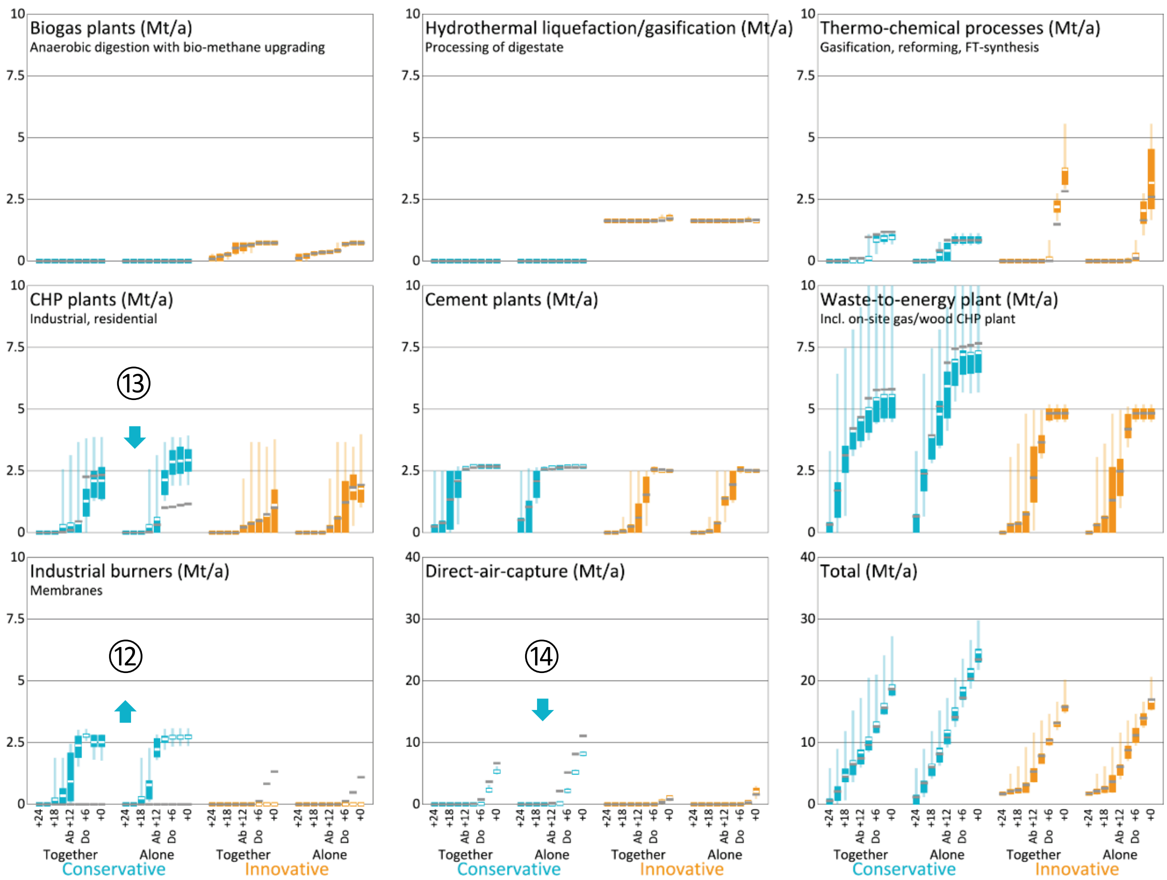


Figure 70: CO2 separation for base scenarios (median shown in grey) and new scenarios <u>with/without membranes</u> for CO2 separation.

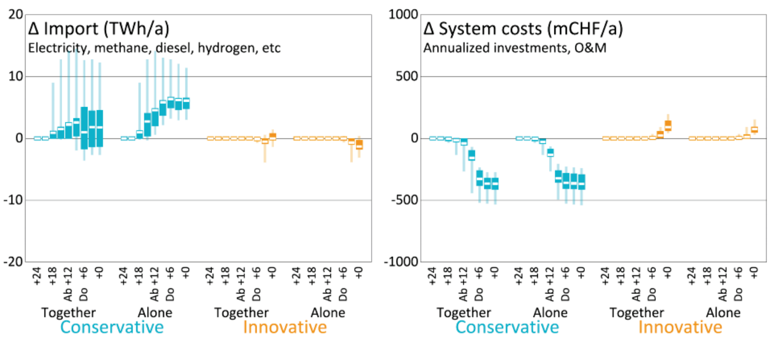


Figure 71: Variation of imports and total system costs of conservative/innovative scenarios <u>with/without membranes for CO2 separation</u> with regards to baseline scenarios.

## 5.5 Flexibility

A variety of flexibility options exist in the energy system. The first three in Table 4 are related to sector coupling, i.e. the connection of electricity with the mobility and heating sector. Their flexibility comes from two sides, one related to power, the other to energy. In case of a battery electric vehicles (BEV) the power is the charging station, the energy the size of the battery. For a heat pump the power is the capacity of the heat pump, the storage the size of a thermal storage. For these we assume that the storage is limited to a few hours or a day. The last options is pumped hydro storage. Note that electrolysis as another sector coupling technology is not present, for the practical reason that it does not appear in the optimal technology mix for the net-zero scenarios considered here. It is also emphasized that the present study considers flexibility as a short time scale effect, mostly related to the way that photovoltaics is integrated into the energy system. The long term flexibility that falls into the domain of storage lakes, large seasonal thermal energy storage or possibly power-to-X is considered in all scenarios but not analyzed here. Note that we follow the convention to label pure charging of BEVs as V1G, whereas charging and discharging (vehicle-to-grid) of BEVs is termed V2G.

Table 4: Flexibility options.

| **Flexibility option** | **Power** | **Energy** |
|---|---|---|
| Battery electric vehicle | Charging station | Car battery |
| Industrial electric heater | Transformer, resistance heater | Short term thermal storage |
| Residential heat pump | Heat pump | Short term thermal storage |
| Pumped hydro storage | Pump / turbine | Upper and lower reservoir |

In a simple model like SES-ETH any element represents always the ensemble of identical elements in the energy system: one air-source heat pump stands for all air-source heat pumps, one gas turbine for all gas turbines, etc. This is generally not an issue except for battery electric vehicles (BEV). Any BEV has fundamentally two different states: (i) it is connected to a charging station and therefore stands still, or (ii) it is not connected and drives or stands still. No single BEV can drive while it is charging.

However, if one BEV shall represent all BEVs, this strict rule cannot be obeyed. Figure 72 illustrates the concept. It shows 8 BEVs and their charging and driving pattern during one day. For saving computational time, the 24 hours are condensed into 8 x 3 hour blocks. Obviously, any single BEV obeys the rule of either charging or driving, but the sum of the 8 BEV does violate the rule. When representing BEVs in a model like SES-ETH we therefore have to imagine a virtual BEV that can charge and drive at the same time. Practically, this virtual BEV is modelled as a battery of a certain capacity with a given peak charging power. This battery is charged using grid electricity and is discharged to provide a mobility service (V1G).

Figure 73 further illustrates this concept. The virtual BEV of Figure 72 is split into the driving and charging operation. It becomes clear that the battery (as sum of all 8 batteries) charges and discharges at the same time. This will not happen in an energy system model, therefore only the balanced battery operation is relevant, which shows clearly that the battery overall delivers energy at the beginning and end of the day and receives energy during midday. Adding this battery operation to the charging and driving patterns finally shows the way BEVs are modelled in SES-ETH.

The energy and power (charging) capacity of this battery needs to be properly defined. We assume that the largest part of Switzerland's fleet of some 5 mio vehicles will be electrified in 2050. Assuming a reasonable battery capacity of 400 km or 80 kWh, the total capacity will be some 400 GWh, roughly the order of magnitude of all pumped hydro storage plants. The maximum charging capacity is harder to estimate. Here we make the crude assumption that at any given time at least 10% of the BEVs are connected to a charging station with a charging power of 10 kW each. This gives a total charging power in any given moment of at least 5 GW. Assuming a higher charging power of 50 kW, only 2% of the cars would need to be connected.

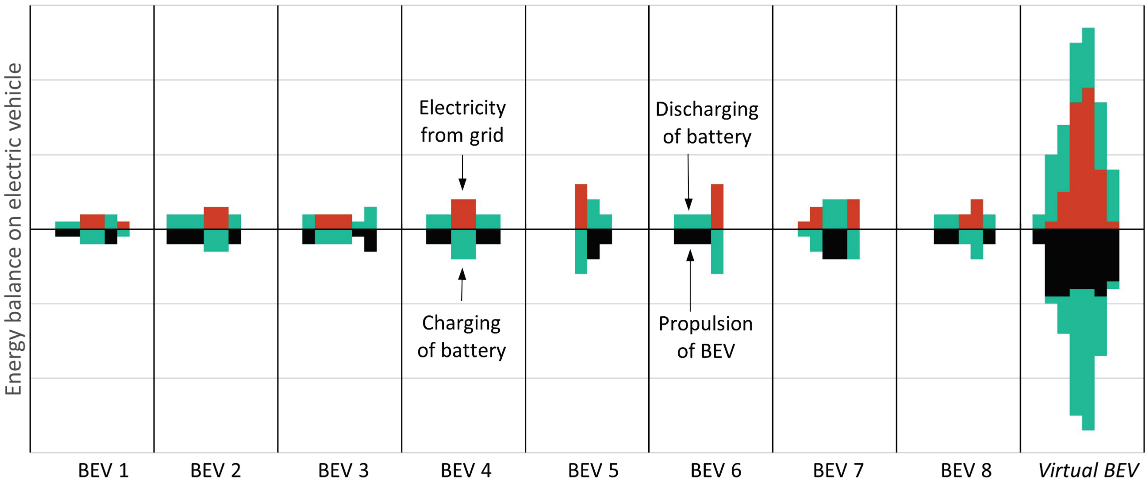


Figure 72: Virtual BEV as sum of several real BEVs.

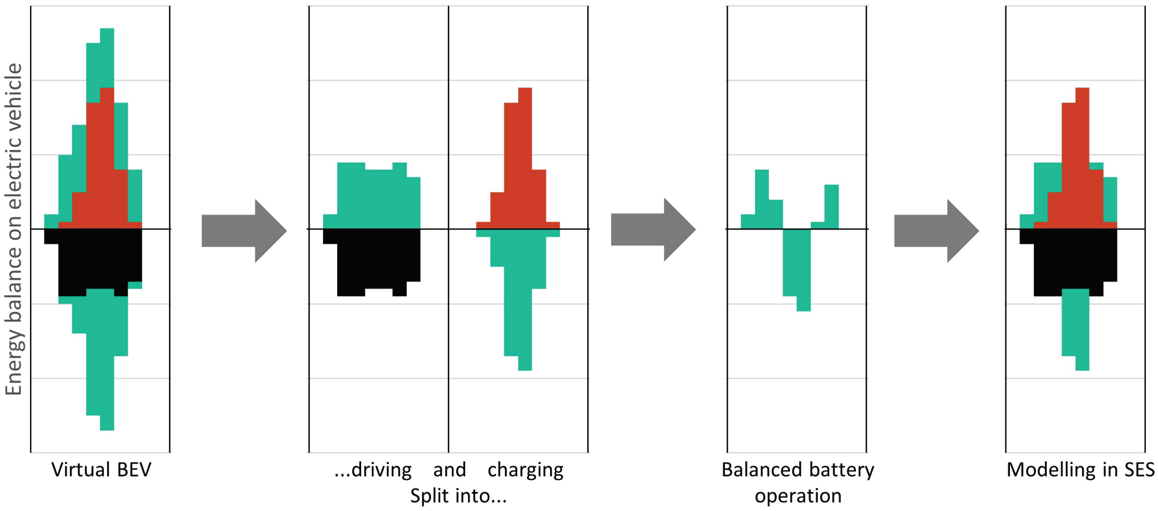


Figure 73: Modelling of BEV is SES-ETH.

Starting from the baseline scenarios we first analyzed two variants, one with unlimited charging power, the other with a charging power that is enforced to be constant over any typical day. Figure 74 shows a few indicators and how they change with respect to the baseline scenarios (middle). The top graph illustrates what happens when flexibility of BEV charging is limited ①. Apparently, the other flexibility providers – pumped hydro storage ②, industrial heaters, domestic heat pumps – take over this role. Here we take the energy that is discharged over a year as a proxy for flexibility provision. Another effect is the reduction of photovoltaic generation ③ and the increase of imports ④. The opposite effect can be observed when the charging flexibility – i.e. the maximum charging power – is unlimited. In this case, the flexibility provision of industrial heaters and heat pumps is decreased, while photovoltaic generation increases. A tentative interpretation of these results is that (i) the flexibility of BEV charging is beneficial for the integration of photovoltaics that in turn leads to a lower demand for energy imports, and that (ii) this flexibility service can to some extent be compensated by the flexibility of the other elements. There seems to be a market for flexibility where different bidders offer their service.

Looking at Figure 74 it seems that pumped hydro storage is the most active flexibility provider besides BEV charging. We therefore performed a second set of simulations where pumped hydro storage is completely removed from the mix. Figure 75 shows the results for this experiment. The picture is qualitatively similar to the previous one, however, the effect of not having BEV charging flexibility available has an even more dramatic effect on the integration of photovoltaics and the need for energy imports. Now it is clear that the flexibility of both BEV charging and pumped hydro storage cannot be compensated by the other flexibility providers, namely industrial heaters and domestic heat pumps. Obviously, the service of pumped hydro storage offers cannot completely disappear, what we simulate with this crude experiment is a situation where the photovoltaic generation that happens mostly in the distribution grid level cannot reach the pumped hydro station at transmission level, i.e. a scenario where the grid is insufficient to manage the energy flows coming from photovoltaics. When considering the middle and lower part of Figure 75 it becomes clear that BEV charging flexibility can compensate for this insufficient grid.

The same trends can be seen in the time series of Figure 76 to Figure 79: reducing the flexibility of BEV charging is compensated to some extent by larger flexibility of industrial electric heaters and pumped hydro storage. Finally, Figure 80 and Figure 81 display the difference in total imports and total system costs referred to the base line scenarios for the case with and without pumped hydro storage, respectively. It becomes clear that removing flexibility increases costs and imports.

**We carefully draw the tentative conclusion that BEV charging can significantly influence the need of electricity grid expansions. This subject needs to be analyzed with tools that are more appropriate than a simple energy system model as SES-ETH. This is planned within SWEET-PATHFNDR.**

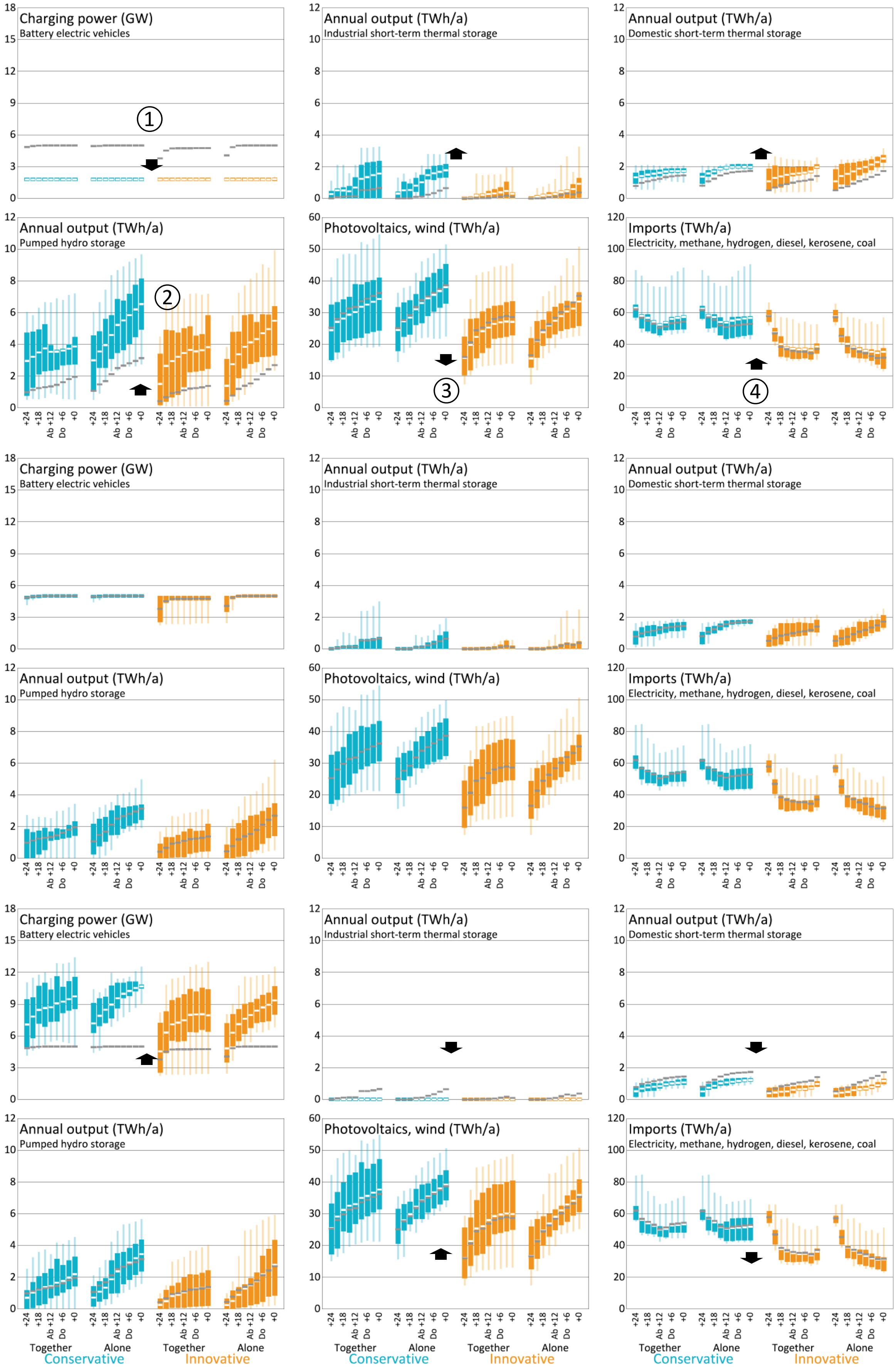


Figure 74: Different indicators compared to baseline scenarios (median in grey); (top) maximum charging flexibility, (mid) baseline charging flexibility (5 GW), (bottom) constant daily charging profile.


Figure 75: Different indicators compared to baseline scenarios (median in grey) without pumped hydro storage; (top) maximum charging flexibility, (mid) baseline charging flexibility (5 GW), (bottom) constant daily charging profile.

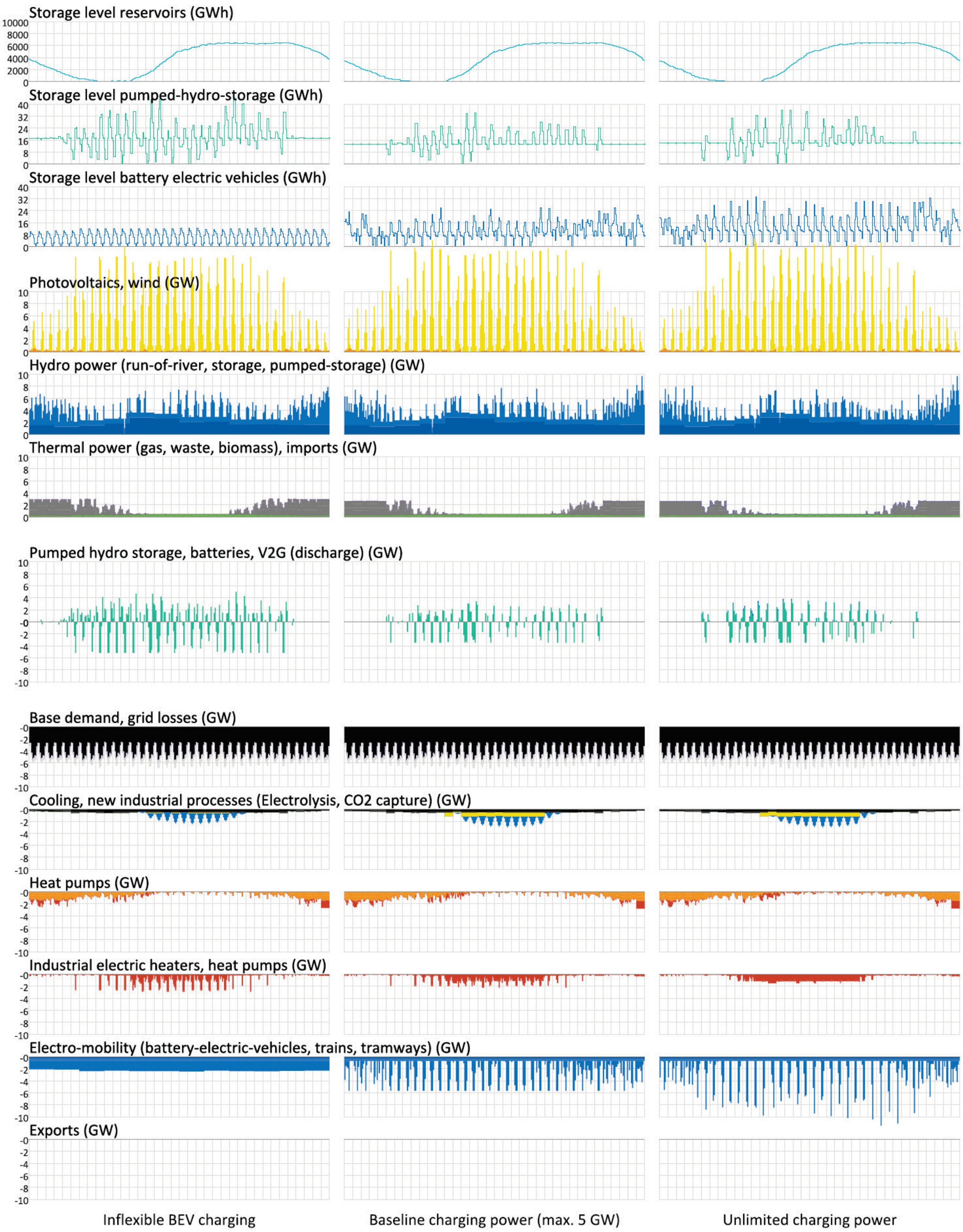


Figure 76: Electricity generation and consumption for a typical Alone/Conservative scenario at 6 $Mt_{CO2}$/a (Domestic); different cases for BEV charging flexibility.

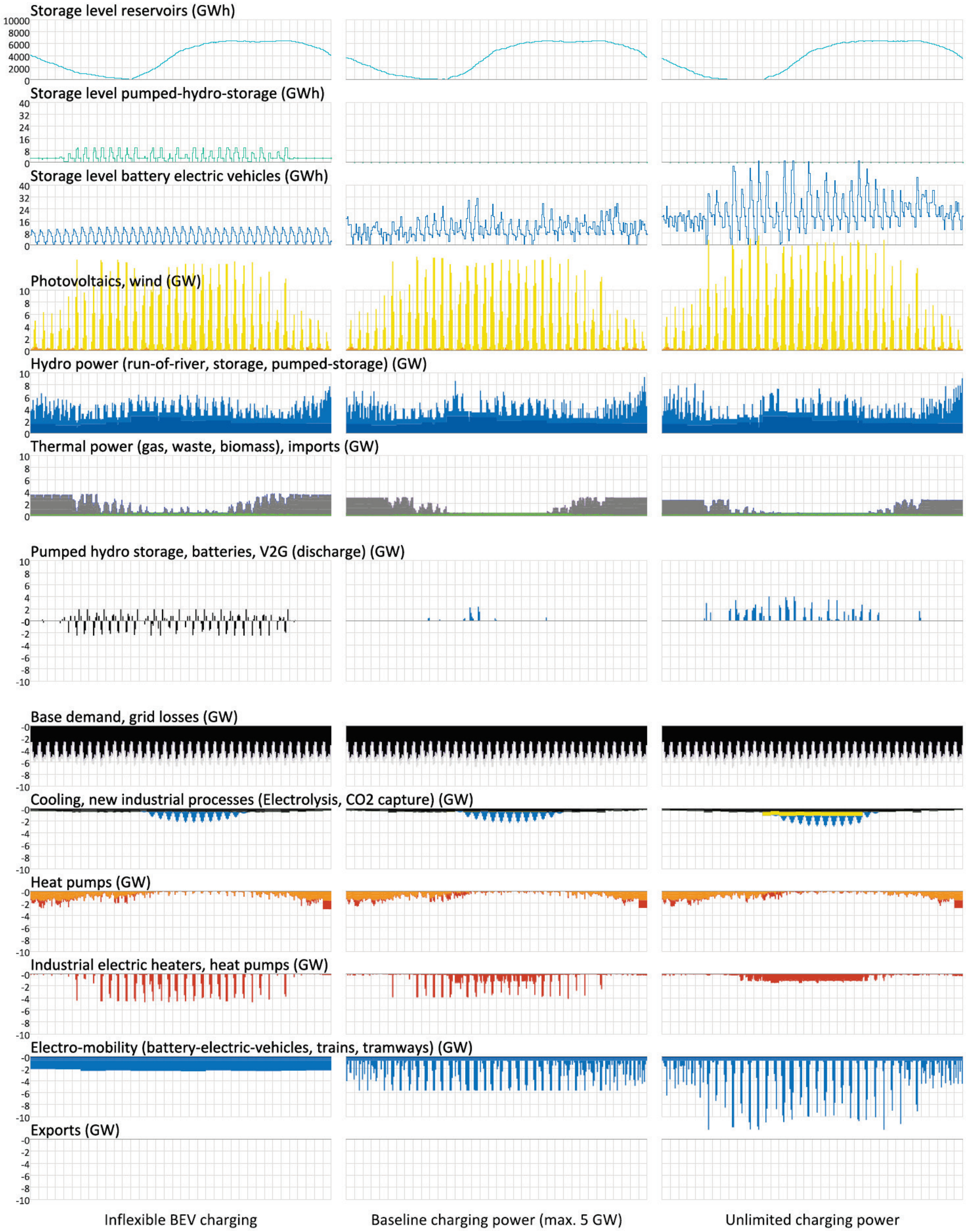


Figure 77: Electricity generation and consumption for a typical Alone/Conservative scenario at 6 $Mt_{CO2}$/a (Domestic); different cases for BEV charging flexibility; without pumped hydro storage.

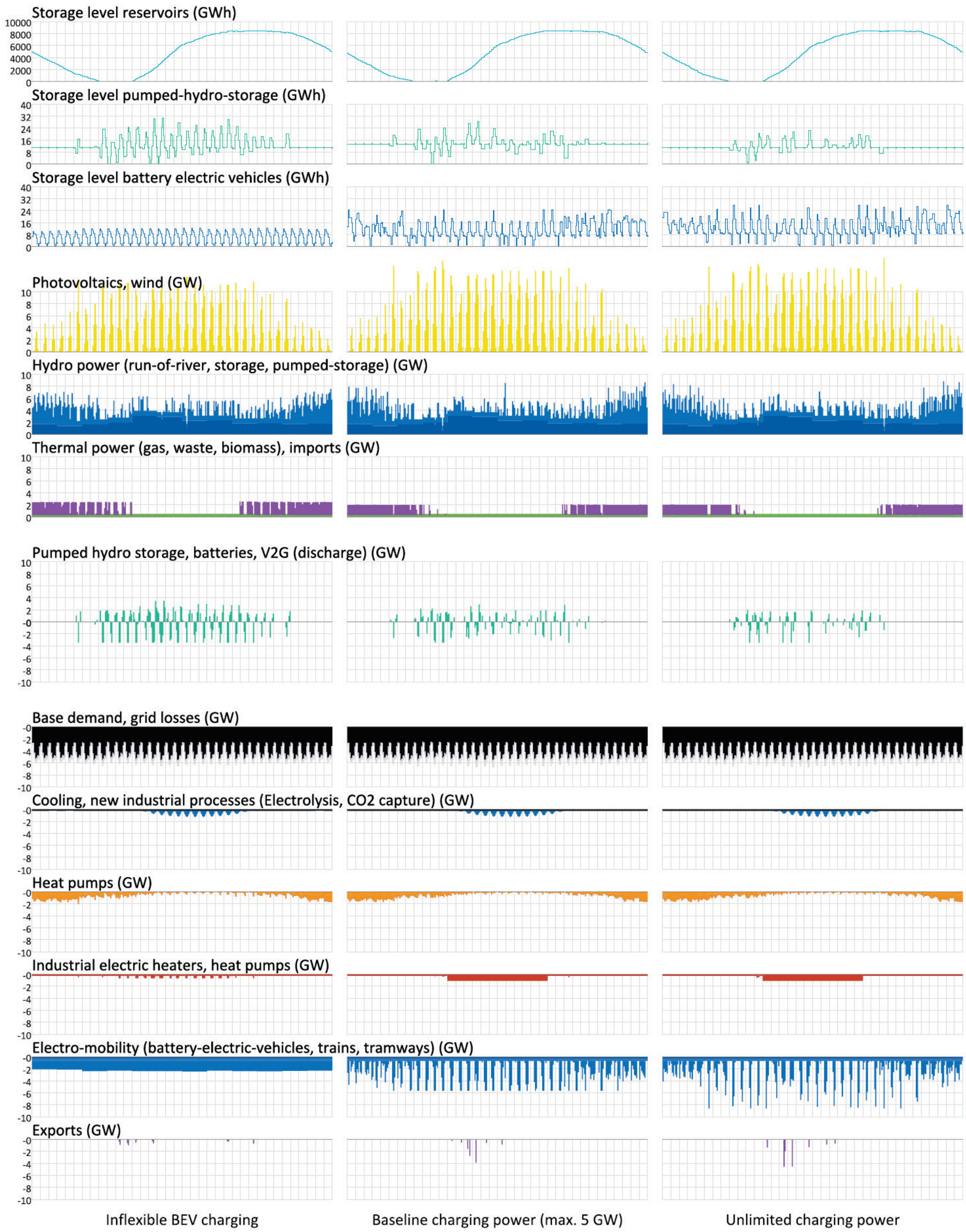


Figure 78: Electricity generation and consumption for a typical Together/Innovative scenario at 6 $Mt_{CO2}$/a (Domestic); different cases for BEV charging flexibility.


Figure 79: Electricity generation and consumption for a typical Together/Innovative scenario at 6 $Mt_{CO2}$/a (Domestic); different cases for BEV charging flexibility; <u>without pumped hydro storage</u>.

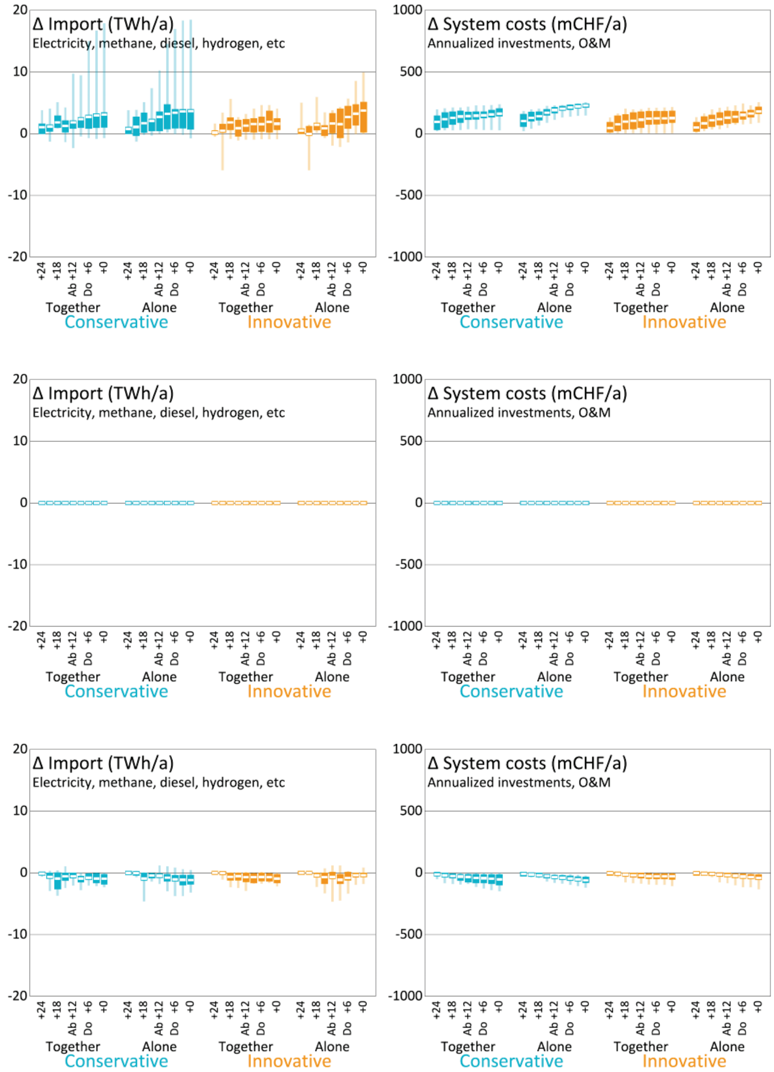


Figure 80: Variation of imports and total system costs with regards to baseline scenarios; (top) maximum charging flexibility, (mid) baseline charging flexibility (max 5 GW), (bottom) constant daily charging profile.

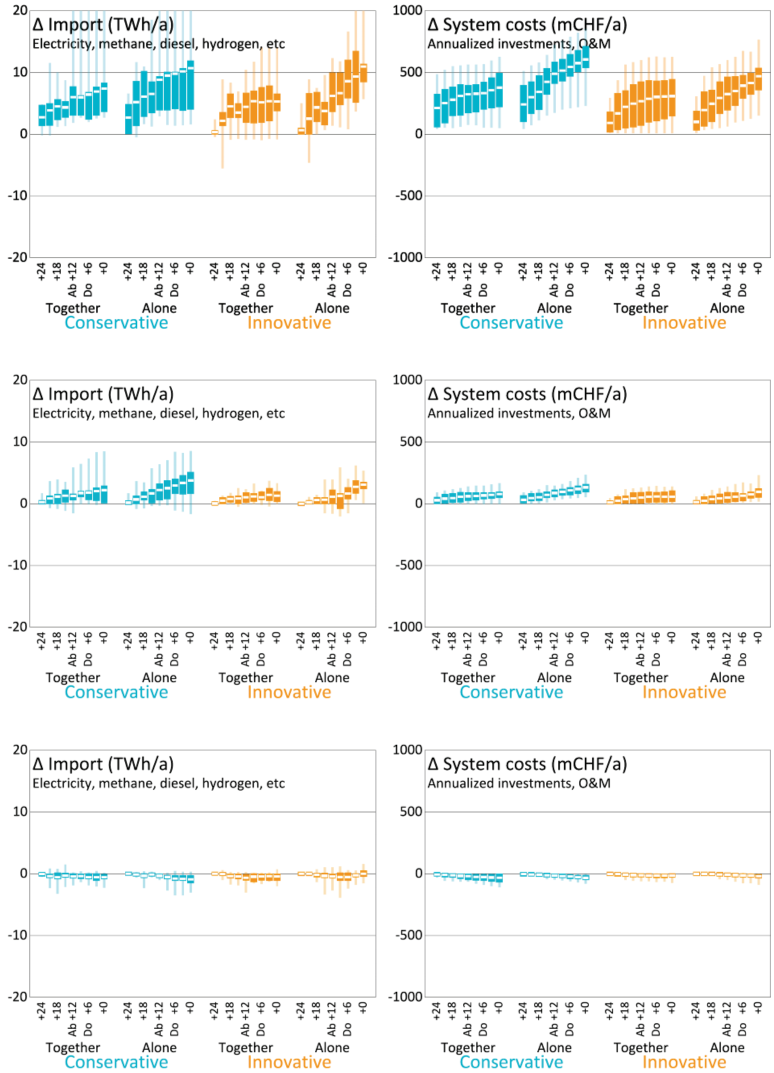


Figure 81: Variation of imports and total system costs with regards to baseline scenarios <u>without pumped hydro storage</u>; (top) maximum charging flexibility, (mid) baseline charging flexibility (max 5 GW), (bottom) constant charging profile over day.

## 5.6 Negative emissions by using wood as a construction material

The proper use of wood is a highly debated subject with large relevance for the energy transition. Options range from domestic pellet boilers to industrial CHP units, cement plants, pyrolysis, gasification and finally the non-energetic use as construction material. The latter offers the prospect of generating negative emissions by storing CO2 in the form of building material. However, the validity of this approach is questioned with the argument that the storage is not "forever" but only as long as the lifetime of the building.

We think that this argument is not valid. Consider the situation for geological CO2 storage as illustrated in Figure 82. After a ramping up phase, some 10 $Mt_{CO2}$/a are stored (see Figure 26). This continues for decades but surely not forever. The level of the CO2 storage will grow and then reach a plateau when storage sites will become expensive. Despite this fact it is common practice in the modelling community (including the present work) to consider the situation when CO2 is stored as a "temporary-stationary" process, i.e. as a process that could in principle continue forever. It is clearly understood that this is not possible, it seems however justified given the question at hand, namely to find out whether CO2-storage can/should play a role for reaching net-zero by the middle of the century.

Now consider the case of storing CO2 in the form of wood buildings. The situation is similar: a storage is filled up with time until a plateau is reached. This plateau is given by the maximum amount of wood buildings that can reasonably be build, and it is reached when the construction of new buildings is equal to the demolition of old buildings. It is indeed true that the CO2 stored in a building will be released after its demolition, but this is compensated by the replacement building that is built at the same time. Therefore, there is no fundamental difference between the geological storage of CO2 and the storage of CO2 in buildings. If we consider the "temporary-stationary" process of CO2 storage as valid we have to allow the same for wood buildings, again considering that the question to be answered is whether or not this option helps to reach the net-zero by the middle of the century. It should be added that in case of wood constructions there is one more effect to be considered, namely the displacement of other construction material such as concrete which has in turn an effect on the CO2 emissions from cement production – or the energy requirements for avoiding these via CCS.

As explained in Section 3, Table 3 we consider using wood as construction material in the innovative scenarios and exclude it from the conservative ones. As before we switch this by assigning wood construction to the conservative scenarios and removing it from the innovative ones. The effect on the usage of wood can be seen in Figure 83. When wood construction becomes available in the conservative scenarios it is used up to its maximum for low CO2 targets ①. This amount is taken away from different types of combustion processes ②. When wood construction is removed from the innovative scenarios, this amount is used for combustion and gasification. Figure 84 shows again the variation of total imports and total system costs. There is a clear benefit on the latter when wood construction becomes available, however, in contrast to other innovative technologies in this section, using wood outside the energy system increases the need for energy imports, mostly methane.

The important takeaway is that whenever wood as construction material is available as option, it is beneficial for achieving net-zero in a cost optimal way. It is indeed true that wood is a valuable energy carrier but this does not mean that it must be used energetically at all costs. This can also be seen in the bottom right of Figure 83: for the generally more restricted conservative scenarios, wood is used up to the maximum whereas in the innovative scenario the maximum use is only reached for 0 CO2 emissions. **In summary, our results indicate that using wood as a building material is beneficial for reaching the Swiss climate goals.**

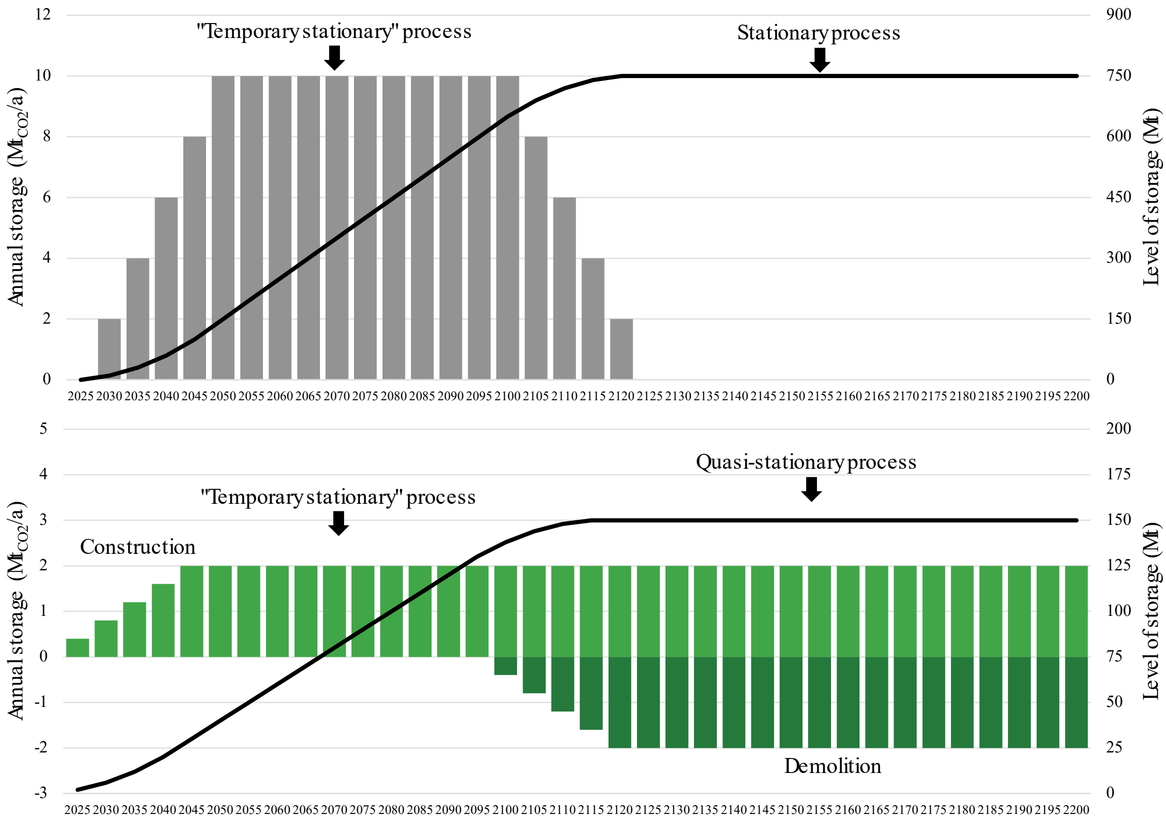


Figure 82: Transition process for geological CO2 storage (top) and CO2 storage in buildings (bottom).

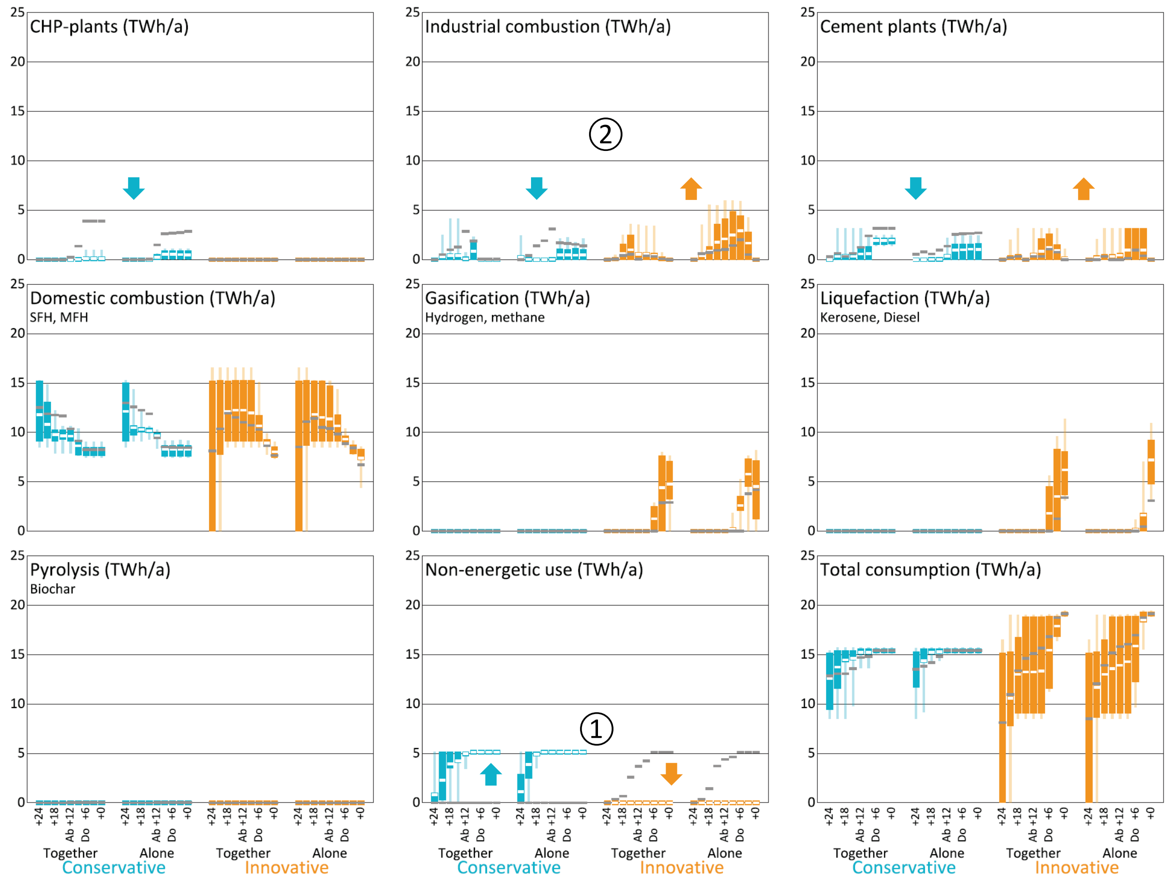


Figure 83: Usage of wood for base scenarios (median shown in grey) and conservative/innovative scenarios with/without wood as construction material.

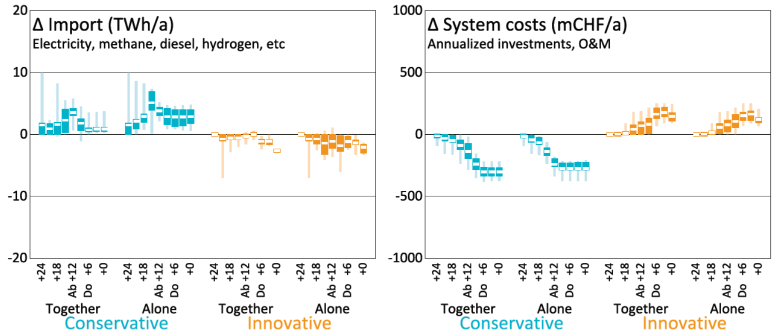


Figure 84: Variation of imports and total system costs of conservative/innovative scenarios <u>with/without wood as construction material</u> with regards to baseline scenarios.

# 6 Disturbances to the energy system

The base scenarios described in Section 4 provide important insights into the key elements of a future energy system. The stability of these insights is considered by having a large number of variants. Generally, those possible futures can be considered moderate, even in the most conservative ones, where we do not consider electricity imports, net-zero can be reached, and it is clear that some of the innovative features are in our hands and can be used to further improve the future system.

It is, however, also interesting to study disturbances to the energy system, even if the only purpose is to learn that we want to avoid them. We consider it also insightful to show that the same model that gave a gently balanced net-zero energy system can also produce extreme results when only some minor assumptions are changed. In the next sections we consider two shock scenarios (i) no imports of fossil oil and gas, (ii) no export of CO2, and a number of disturbances, such as (iii) unlimited imports of hydrogen at a low price, (iv) a minimum domestic production of liquid fuels, and (v) the possibility to freely allocate waste as a resource.

## 6.1 No fossil methane and Diesel imports

The first shock scenario assumes that no imports of fossil methane or oil products are available – with the exception of kerosene for aviation which we consider not vital for the functioning of Swiss society. Note that we did not limit the imports of biogas, biofuels or hydrogen as prescribed for the Together scenarios in Table 3. The effect on primary energy imports can be seen in Figure 85. All imports for the Alone scenarios drop to approx. 25 TWh/a which is the level of kerosene imports ①. Figure 86 shows that the lack of methane reduces gas power generation ② and increases photovoltaic generation ③. This is especially evident for the Alone Conservative scenario, which required more methane for electricity generation than the others.

Figure 87 shows that the extra generation is mostly used for electrolysis, especially for the Alone Conservative scenario ④. This can also be seen in Figure 88 which illustrates that electrolysis ⑤ replaces steam methane reforming ⑥ as main hydrogen production technology, simply because methane is no longer available. The extra hydrogen is used for mobility, methanation and power generation (see Figure 89). Figure 90 shows finally the difference in energy imports and total system costs for the scenario of no methane/Diesel imports. It again evident that especially the Alone/Conservative scenarios is critical, leading to an increase of total system costs by 1 bn CHF/a. However, the remarkable conclusion is that for all other scenarios the loss of methane imports has only a minor effect on system costs. In the Together/Conservative case this is achieved by slightly higher electricity imports, while the two innovative cases are not heavily impacted, simply because innovation drives methane imports down already for the base scenarios.

In summary, a true island scenario for Switzerland (no imports of electricity, methane and Diesel) may lead to a significant increase of system costs but this can be controlled by the innovative measures listed in Table 3. Allowing for electricity imports makes it easy to compensate the loss of fossil imports. **It is also worth mentioning that only in the aforementioned island scenario power-to-gas-to-power plays a significant role, meaning that this technology is only important in a situation which should be avoided anyway, preferably by an electricity trading agreement with Switzerland's neighbors.**

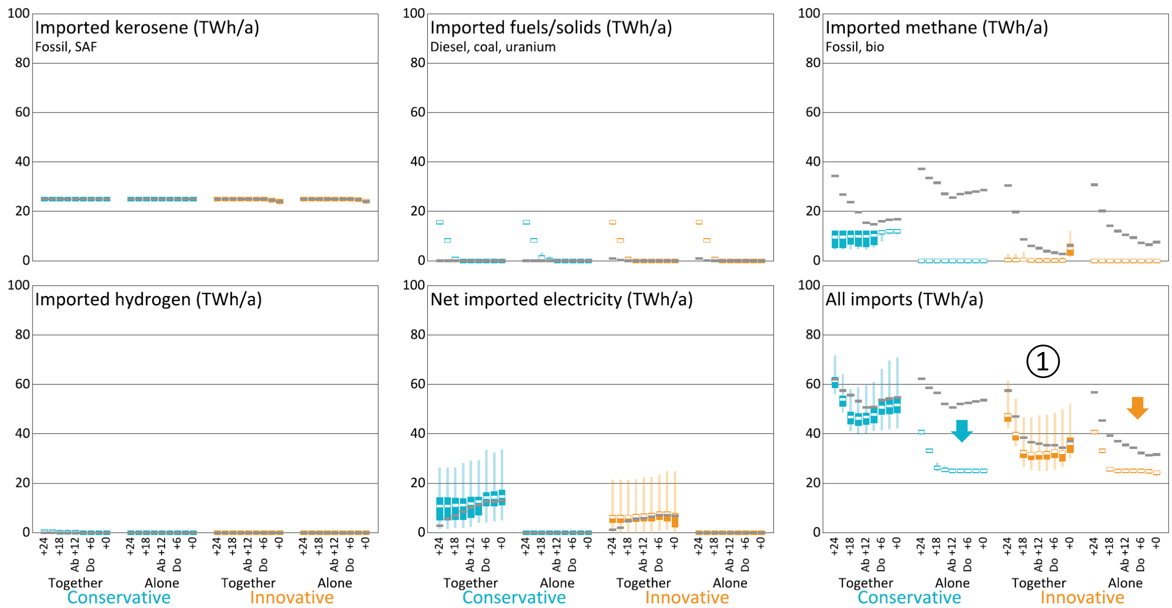


Figure 85: Primary energy imports for base scenarios (median shown in grey) and new scenarios without imports of fossil methane and Diesel.

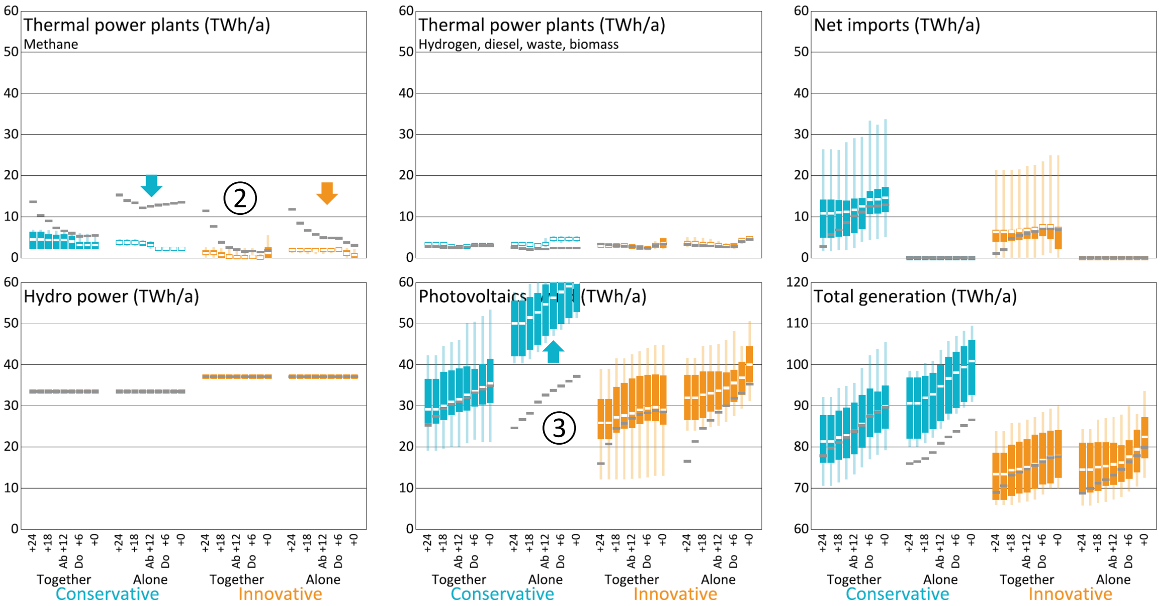


Figure 86: Electricity generation for base scenarios (median shown in grey) and new scenarios <u>without imports of fossil methane and Diesel</u>.

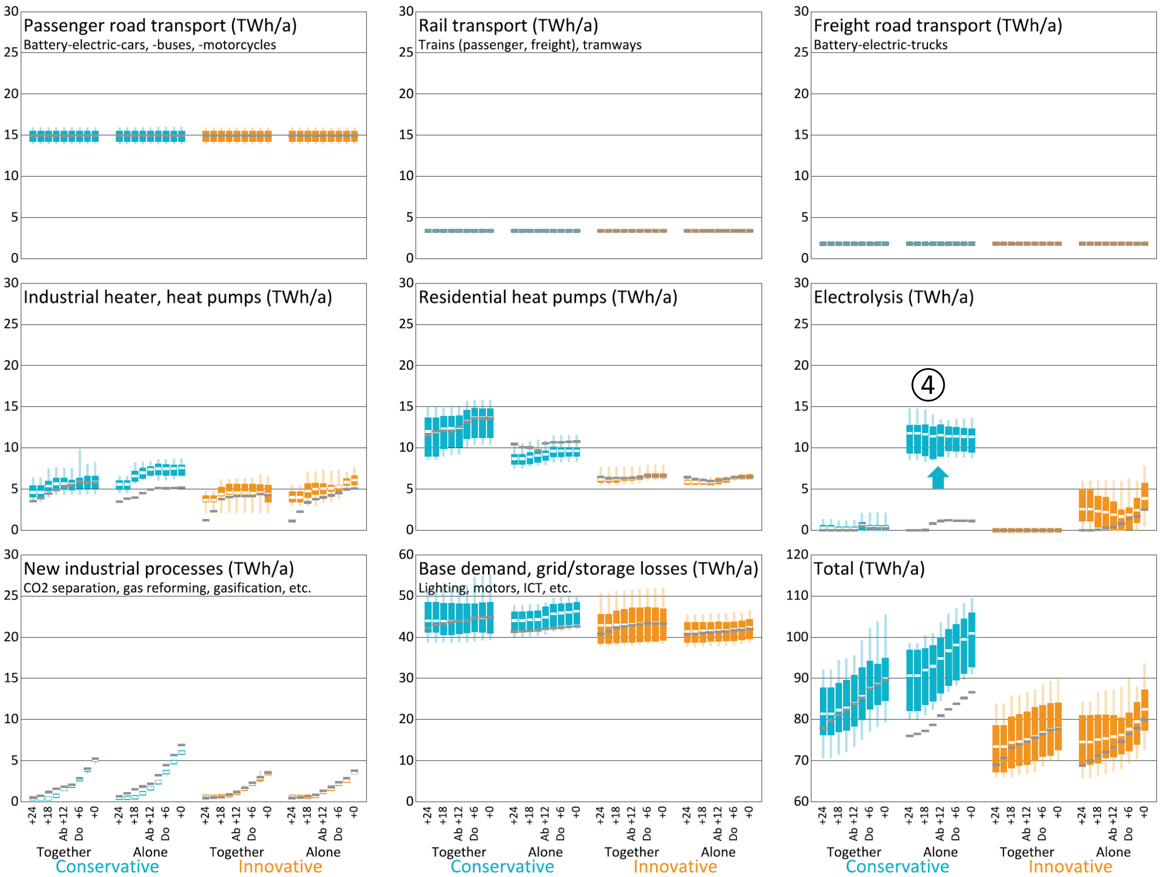


Figure 87: Electricity consumption for base scenarios (median shown in grey) and new scenarios <u>without imports of fossil methane and Diesel</u>.

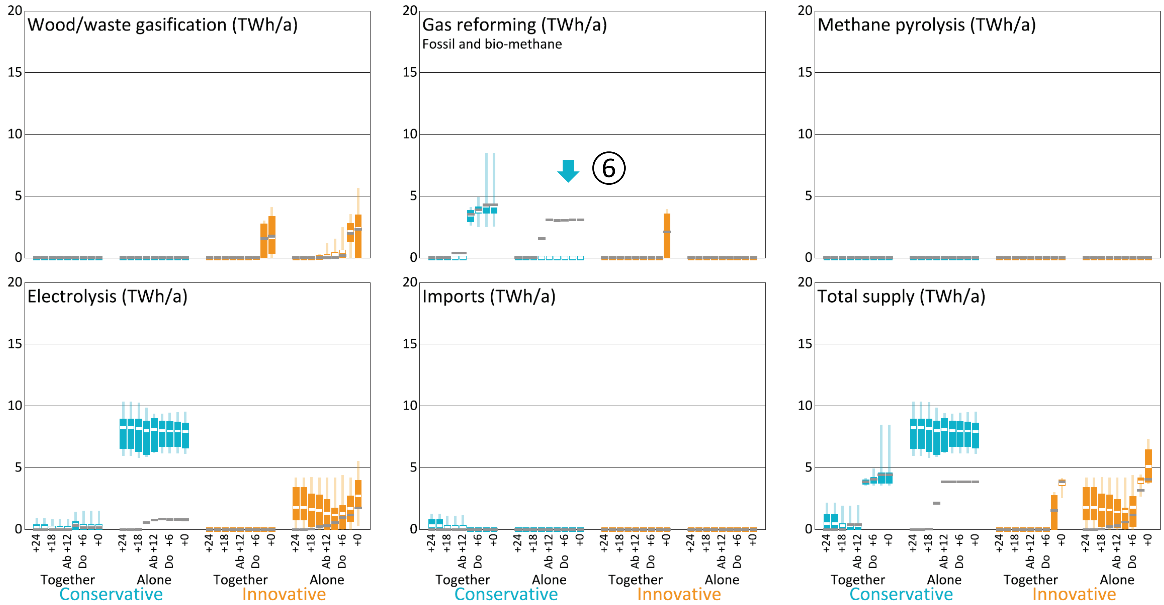


Figure 88: Hydrogen production for base scenarios (median shown in grey) and new scenarios without imports of fossil methane and Diesel.

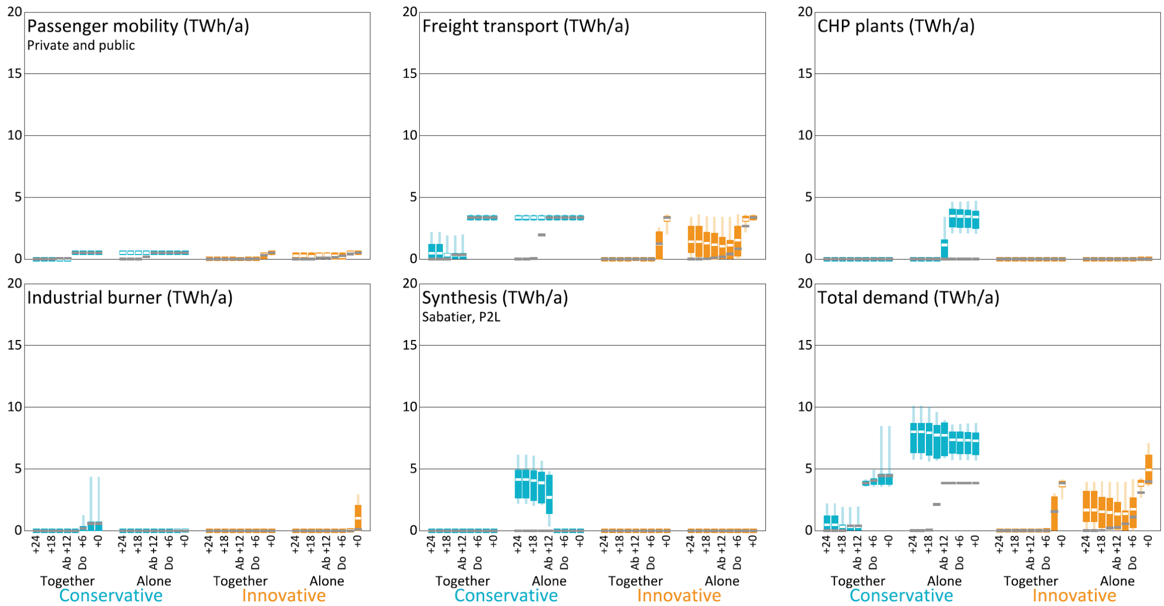


Figure 89: Hydrogen consumption for base scenarios (median shown in grey) and new scenarios without imports of fossil methane and Diesel.

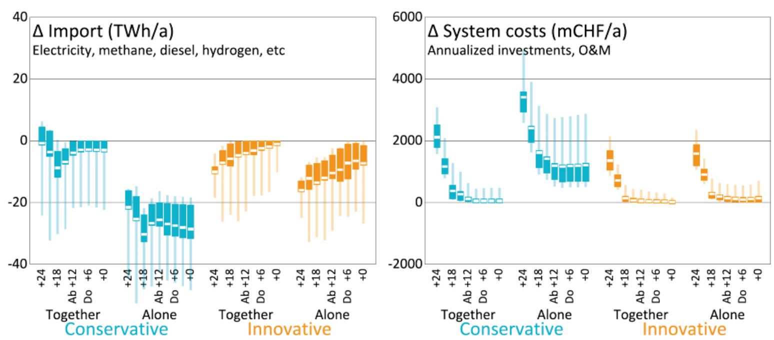


Figure 90: Variation of imports and total system costs of conservative/innovative scenarios without imports of fossil methane and Diesel.

## 6.2 No CO2 exports

The next shock scenario is to consider no export and geological storage of CO2. Here we assume that also a domestic storage is not available at significant quantities. The baseline assumption is that transport and storage from the Swiss border can be realized at a price of 100-200 CHF/tCO2. We model the shock by increasing this price by a factor of 100. This forces the model to realize all other options for reducing CO2 emissions before CO2 export and geological storage is taken as the last option.

Figure 91 shows the different storage options of CO2, i.e. geological storage, and storage in the form of carbon or wood. We distinguish three regimes in the following figures: (i) no geological storage is required, therefore the absence of storage does not impact the results and the shock scenario is identical with the baseline, (ii) geological storage is used in the baselines scenarios but an alternative is found for the shock scenario, here the shock scenario departs from the baseline, (iii) geological storage is required despite the high costs, i.e. no alternative is available anymore and there is no feasible solution within the context of no geological CO2 storage. Those solutions are removed from the result plots and the area is marked with a grey shading. We can see that in contrast to the baseline scenarios, the storage in the form of carbon from pyrolysis is chosen at the maximum of 2 $Mt_{CO2}$/a ①. Also wood construction contribute with 2 $Mt_{CO2}$/a.

It is interesting to explore what the model does differently in the intermediate zone between the onset of CO2 storage in the baseline and shock scenarios. Figure 93 illustrates that CO2 reduction is now achieved by producing synthetic fuels for aviation and Diesel as a by-product ②. This requires a number of shifts in the energy system, most notably a huge increase of photovoltaic generation ③ (Figure 95) and hydrogen production by electrolysis ④ (Figure 94). Also biomass and waste-to-liquid pathways are exploited (Figure 93). A further consequence is a shift from CO2 storage to CO2 usage for the fuel synthesis (Figure 92). Once all aviation fuel is synthetically produced using domestic CO2 and hydrogen, a further reduction of emissions is not possible anymore, and this is the point where geological CO2 storage becomes unavoidable – or there is no feasible solution anymore if CO2 storage is strictly forbidden.

What can be learned from this extreme scenario is the following: not considering geological CO2 storage as an option, decarbonization can only be achieved by massively producing synthetic aviation fuels. This reduces in turn the imports of fossil kerosene to zero but requires a huge increase of electricity production (either through imports or photovoltaics) to generate hydrogen to then produce synthetic fuels. As Figure 96 shows, overall system costs increase by 5-10 bCHF/a. **The clear takeaway from this analysis is that Switzerland has to be connected to a (yet to be build) European CO2 transport and storage infrastructure**.

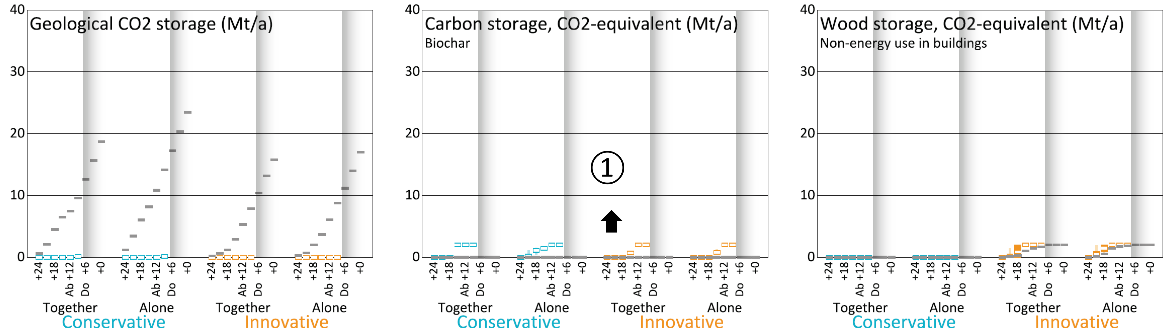


Figure 91: CO2 storage for base scenarios (median shown in grey) and new scenarios <u>without geological CO2 storage</u>.

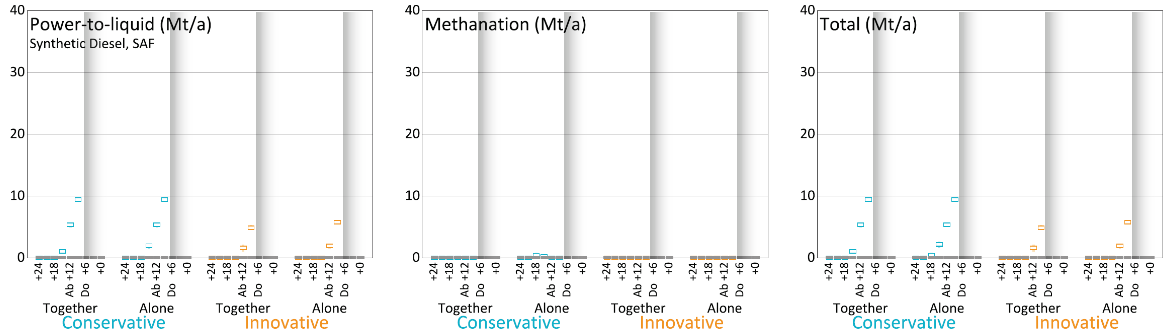


Figure 92: CO2 usage for base scenarios (median shown in grey) and new scenarios <u>without geological CO2 storage</u>.

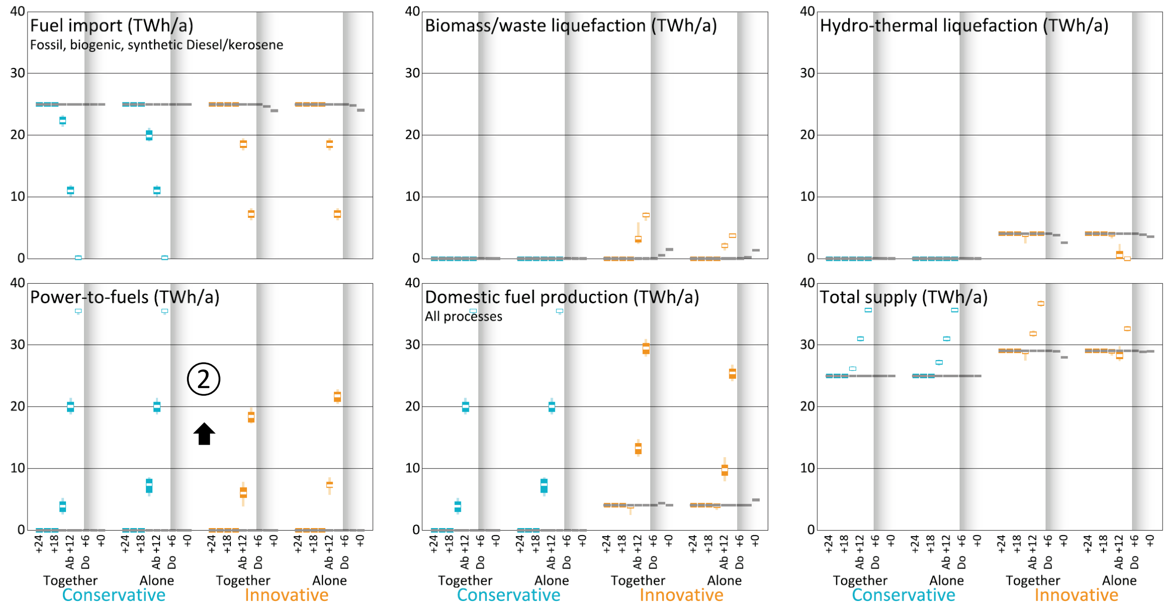


Figure 93: Supply of liquid fuels for base scenarios (median shown in grey) and new scenarios <u>without geological CO2 storage</u>.

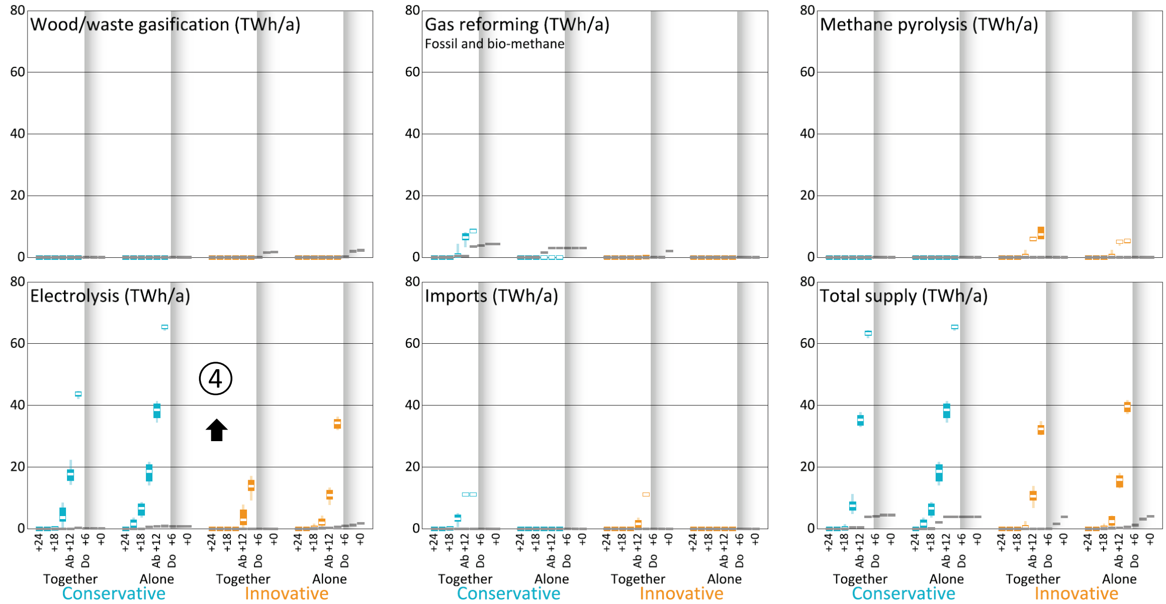


Figure 94: Production of hydrogen for base scenarios (median shown in grey) and new scenarios without geological CO2 storage.

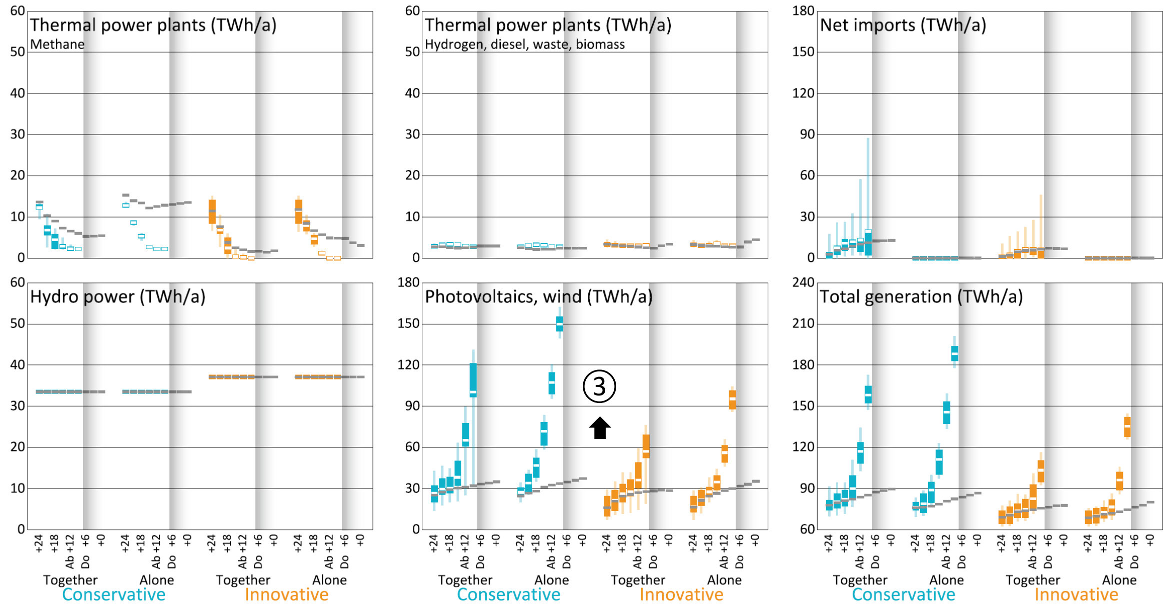


Figure 95: Electricity generation for base scenarios (median shown in grey) and new scenarios without geological CO2 storage.

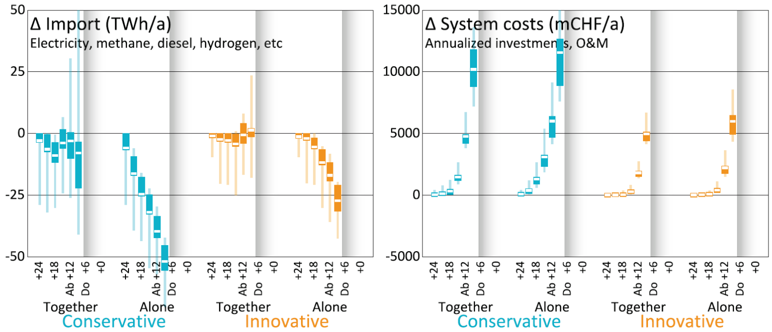


Figure 96: Variation of imports and total system costs of conservative/innovative scenarios without geological CO2 storage with regards to baseline scenarios.

## 6.3 Hydrogen imports at 75 CHF/MWh

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]. We therefore repeat all scenarios with a hydrogen import price reduced to the same 75 CHF/MWh (2.5 CHF/kgH2).

Figure 97 shows how primary energy imports change when cheap hydrogen becomes available. Hydrogen imports increase ①, and replace imports of methane ② and electricity ③. Figure 98 illustrates that this hydrogen is mostly used in CHP plants ④ and for industrial heat generation ⑤. The important role of hydrogen for electricity generation ⑥ can also be seen in Figure 99, where this technology displaces methane fired plants ⑦ and also imports ⑧. Finally, Figure 100 shows the difference in total imports and total system costs when hydrogen becomes available at a low price.

It is interesting to note that the effect of cheap hydrogen is very different for the conservative and innovative scenarios. Whereas imports and electricity generation increase significantly for the conservative scenarios, there is a much smaller effect for the innovative ones. The reason is similar to the situation with no methane imports that was considered in Section 6.1, the imports of fossil methane decline anyway towards the lower CO2 targets, therefore the need for an alternative energy carrier is smaller. This is especially evident in Figure 100, where having cheap hydrogen leads to a massive cost reduction for the conservative scenarios but has a small effect on the innovative ones.

**Independent of whether a hydrogen import price of 75 CHF/MWh is considered realistic, having the option to import hydrogen has a positive effect on the energy system. Switzerland should therefore be connected to a European hydrogen network.**

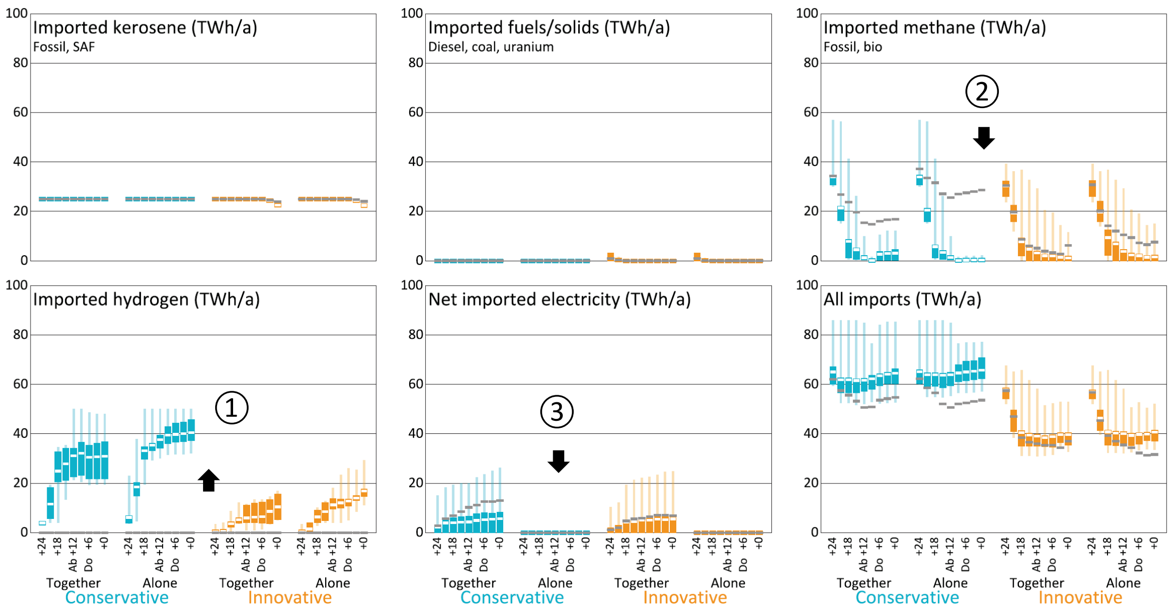


Figure 97: Primary energy imports for base scenarios (median shown in grey) and new scenarios <u>with unlimited hydrogen imports at 75 CHF/MWh</u>.

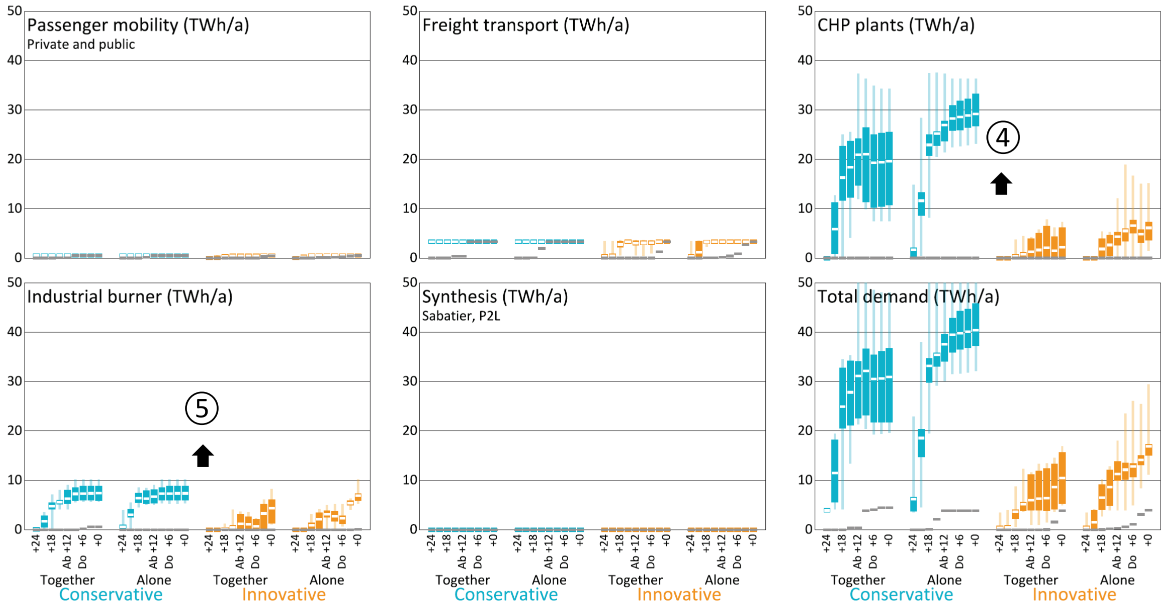


Figure 98: Hydrogen consumption for base scenarios (median shown in grey) and new scenarios <u>with unlimited hydrogen imports at 75 CHF/MWh</u>.

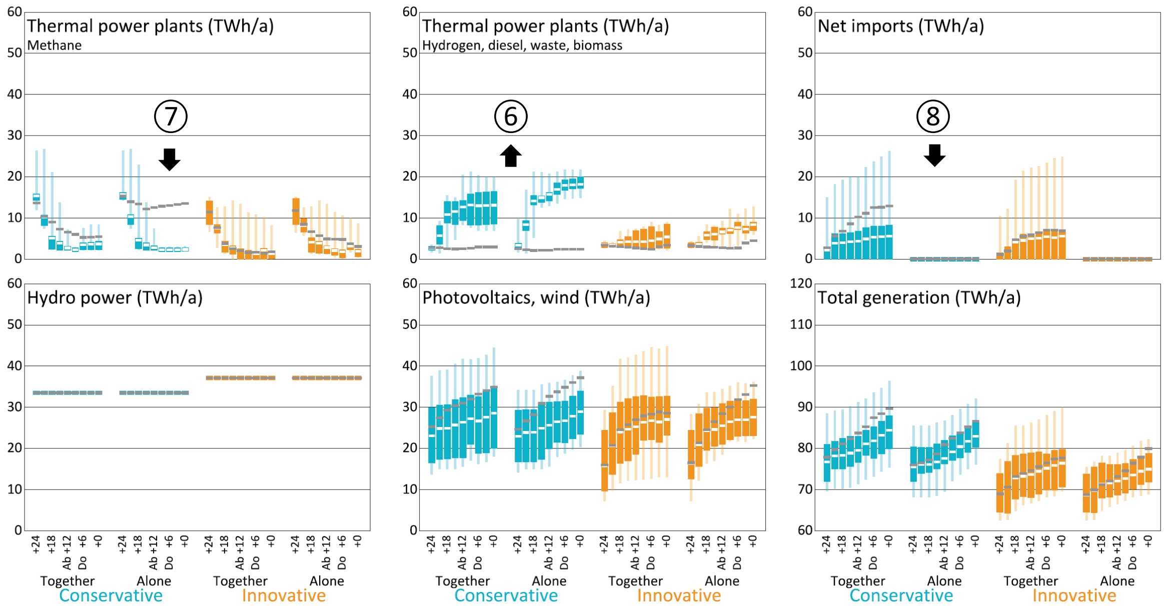


Figure 99: Electricity generation for base scenarios (median shown in grey) and new scenarios <u>with unlimited hydrogen imports at 75 CHF/MWh</u>.

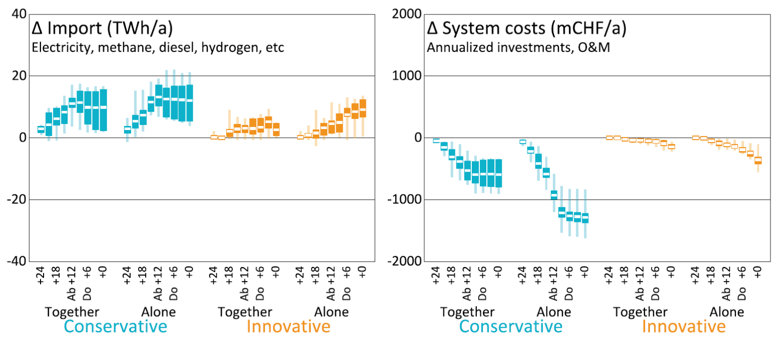


Figure 100: Variation of imports and total system costs of conservative/innovative scenarios for <u>hydrogen imports at 75 CHF/MWh</u> with regards to baseline scenarios.

## 6.4 Minimum production of liquid fuels in Switzerland

The recently started SWEET reFuel.ch project aims at answering the question how Switzerland should be provided with sustainable fuels and platform chemicals in a net-zero future. The present model can explicitly only consider the domestic production of fuels, imports from abroad are treated as a commodity that has a price (and possibly a limited yearly volume). Fuels are Diesel, that can be used for mobility, power and heat generation, and kerosene for aviation. Platform chemicals are not considered presently but will be added in the coming year.

Past research in the VADER project concluded already that a complete production of sustainable fuels in Switzerland would lead to massive increase of electricity demand for electrolysis that supplies then hydrogen for power-to-liquid processes [10]. Such an option cannot be considered realistic as it would lead also to much higher total system costs. The conclusion was that Switzerland should engage into the production and sourcing of sustainable fuels outside Switzerland – and this is precisely the subject of reFuel.ch.

However, the call that led to the project specified also the need to supply some quantity of Diesel and kerosene for the military. It mentions at least 20 mio liter of Diesel and 40 mio liter of kerosene, this being equivalent to 200 GWh and 400 GWh, respectively. Such quantity is almost negligible, therefore we studied a variant of the base scenarios where a total of 1 GWh (100 mio liter) of both Diesel and kerosene should be produced in Switzerland. The processes available for this are power-to-liquid (electrolysis, reaction with CO2, FT-synthesis), biomass-to-liquid (gasification with FT-synthesis) and hydrothermal liquefaction (HTL). The FT-synthesis processes are assumed to produce a maximum of 70% kerosene, the rest being Diesel, the HTL produces only Diesel. As explained in Section 3, B2L and HTX are only available in the innovative scenarios, whereas P2L is always available.

Figure 101 shows the production mix for Diesel and sustainable aviation fuels (SAF), i.e. synthetic kerosene. The picture is indeed very different for the conservative and innovative scenarios. In the latter case the routes via biomass or waste are chosen ① and the synthesis via electrolyzed hydrogen and CO2 is absent from the optimal mix. Only when these biomass pathways are not available, P2L is used in the conservative scenarios ②. The increased need for hydrogen can also be seen in Figure 102 ③ while Figure 103 shows the increased electricity demand for electrolysis ④ in the conservative scenarios.

The overall impact on energy imports and total system costs is summarized in Figure 104. **It shows that especially in the innovative scenarios when biomass/waste routes are available, the domestic production of 100 mio liter Diesel and SAF can be accommodated with minor effort.**

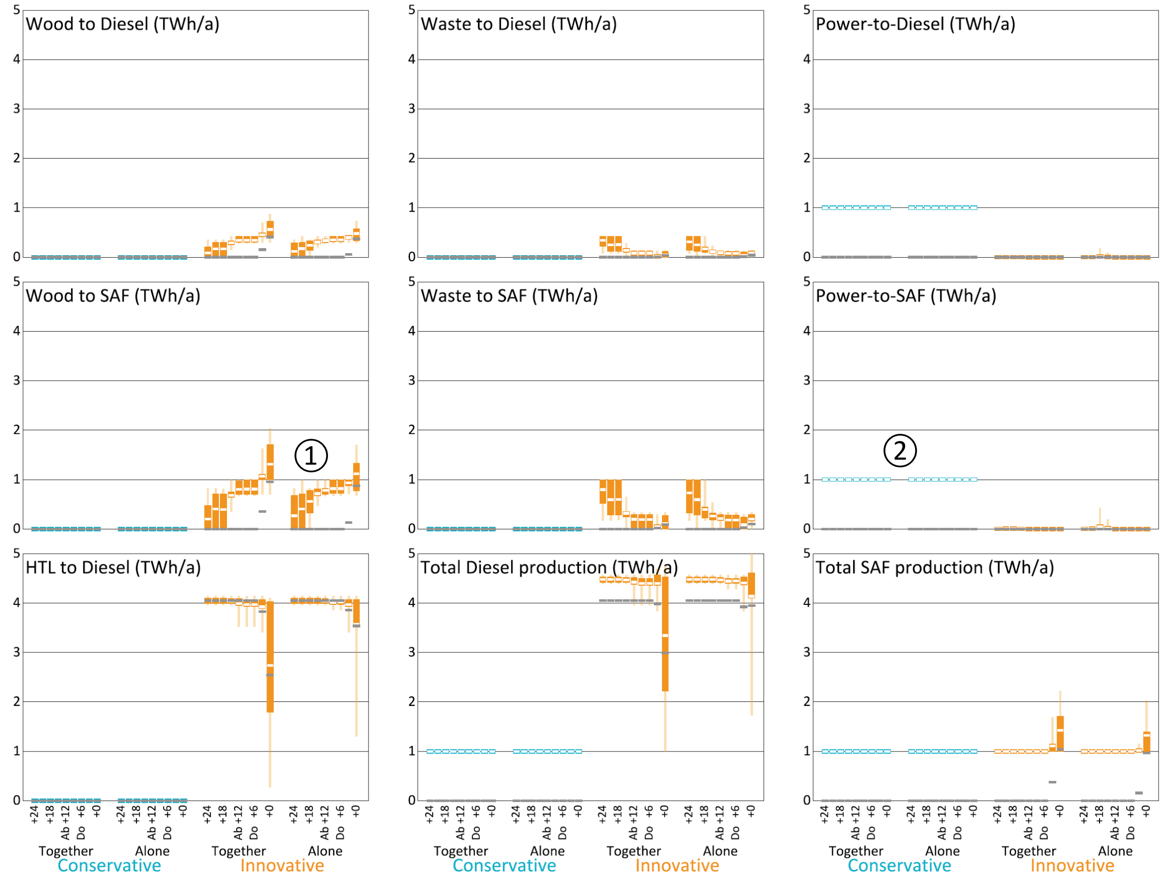


Figure 101: Domestic production of liquid fuels for base scenarios (median shown in grey) and new scenarios with minimum domestic fuel production volume.

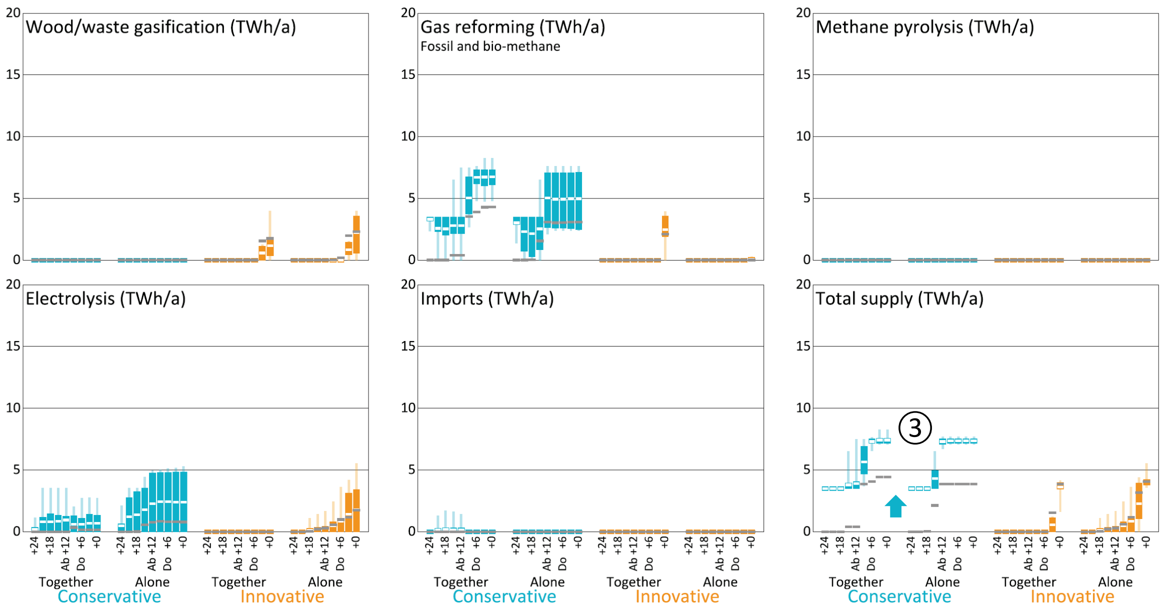


Figure 102: Hydrogen supply for base scenarios (median shown in grey) and new scenarios with minimum domestic fuel production volume.

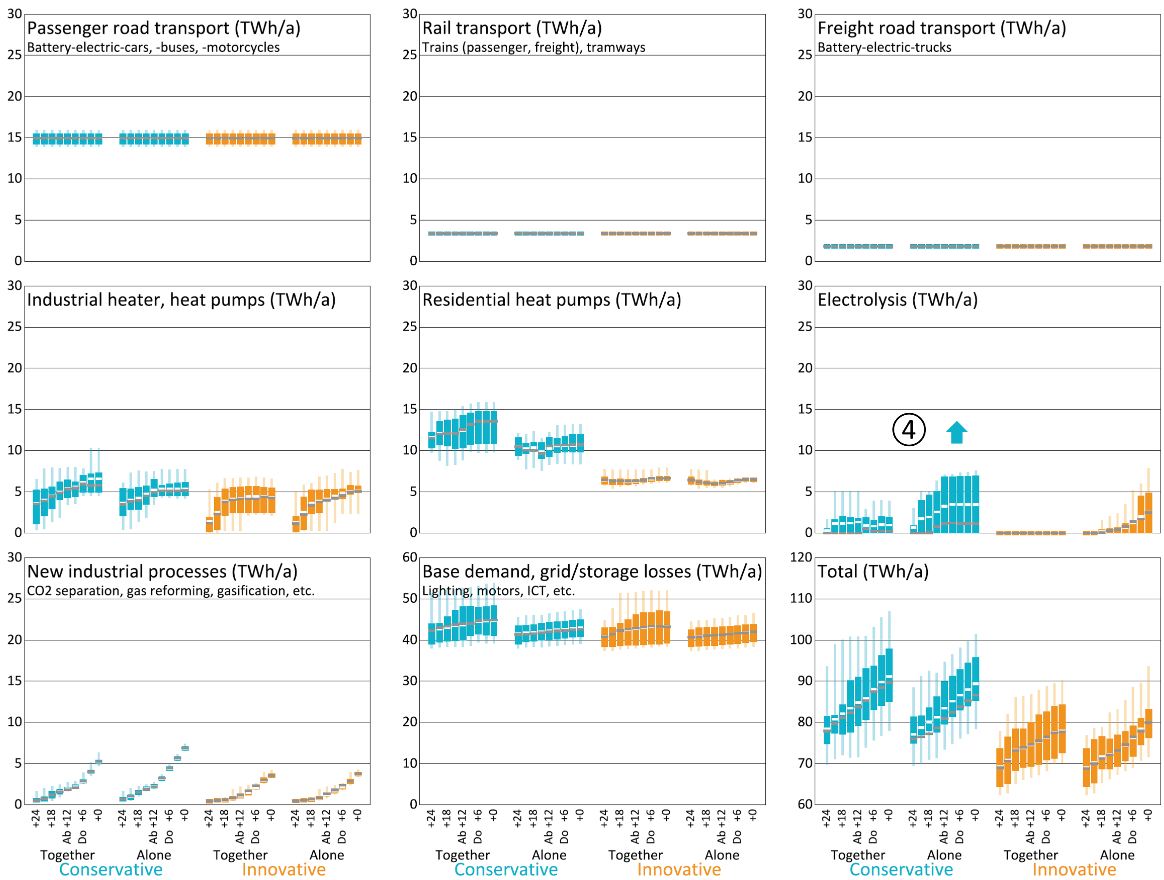


Figure 103: Electricity demand for base scenarios (median shown in grey) and new scenarios <u>with minimum domestic fuel production volume</u>.

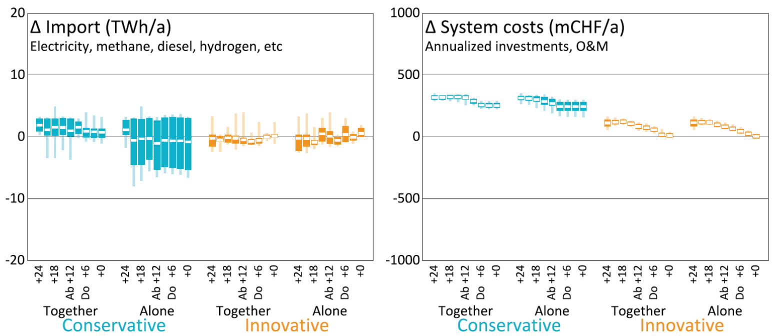


Figure 104: Variation of imports and total system costs of conservative/innovative scenarios <u>with minimum domestic fuel production volume</u> with regards to baseline scenarios.

## 6.5 Free allocation of waste as a resource

As mentioned in Section 4.4, the use of waste as a valuable chemical energy carrier is constrained in the model such that a large portion is allocated for waste-to-energy plants that supply heat via district heating networks. Here it is assumed that little can change until the middle of the century. Nevertheless, it is interesting to study what would happen if this constraint was removed.

Figure 105 shows that waste would indeed be used quite differently, namely to provide industrial heat and as a feedstock for gasification and liquefaction processes – at least in the innovative scenarios when those technologies are available. Today's use to supply low grade heat via district heating networks is not part of the optimal solution. This is not surprising but shows that even a simple energy system model like SES-ETH strives for an exergetic optimization, i.e. an optimal use of a resource like waste for high value applications. Figure 106 shows that most of the waste in the innovative scenarios is used for liquefaction, i.e. to produce a storable liquid energy carrier that can then be used for power and heat generation. Finally, Figure 107 illustrates that total system costs can be reduced.

**In summary, whenever the opportunity arises that waste streams could be reallocated, an application for high temperature process heat or gasification/liquefaction should be considered.**

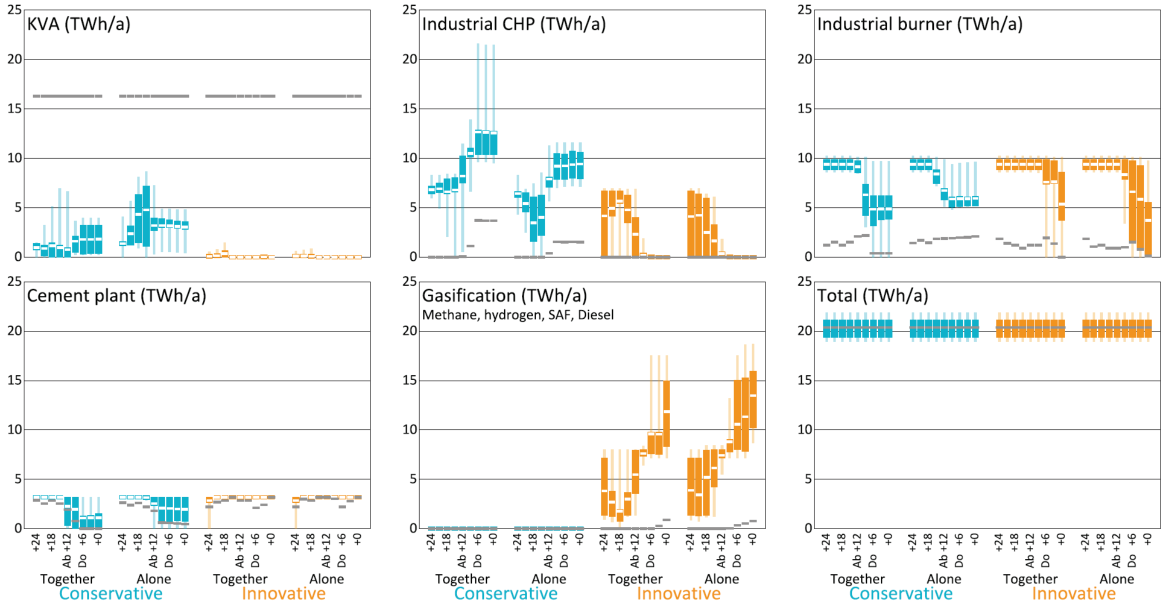


Figure 105: Usage of waste for base scenarios (median shown in grey) and new scenarios <u>with a free allocation of waste</u>.

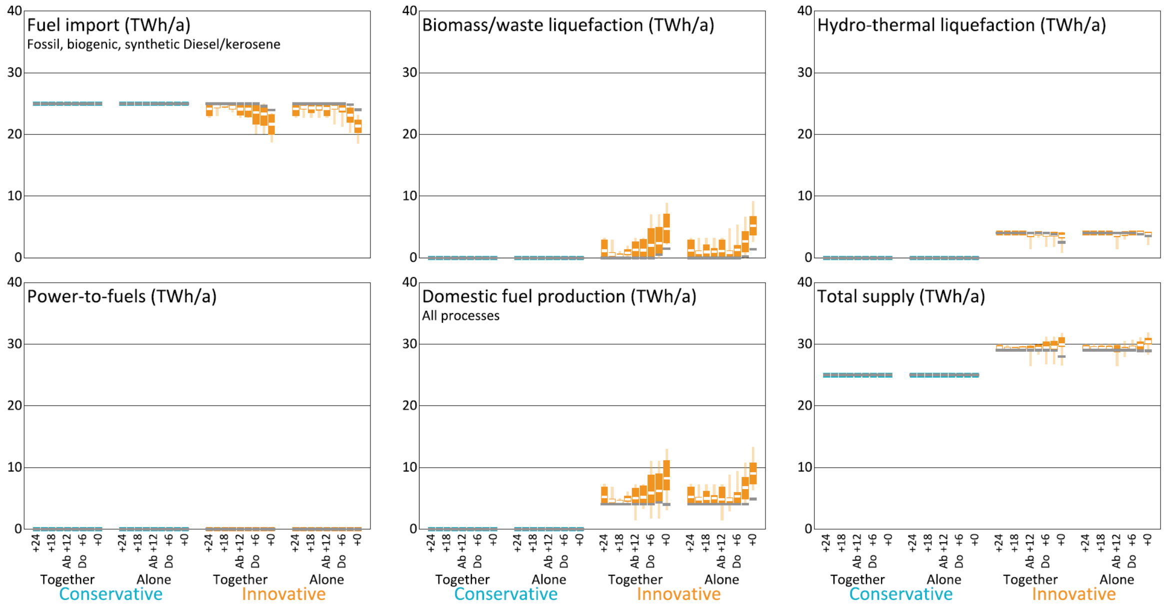


Figure 106: Supply of liquid fuels for base scenarios (median shown in grey) and new scenarios <u>with a free allocation of waste</u>.

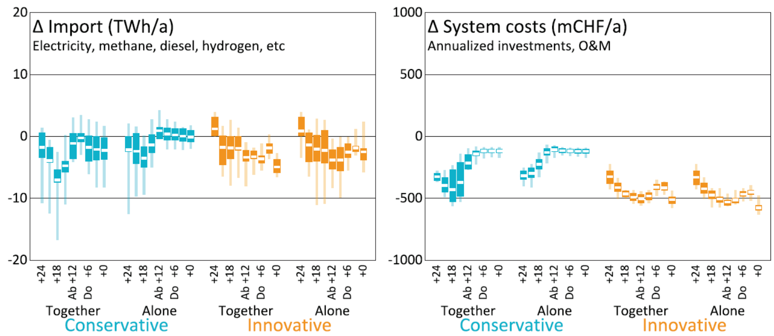


Figure 107: Variation of imports and total system costs of conservative/innovative scenarios <u>with a free allocation of waste</u> with regards to baseline scenarios.

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