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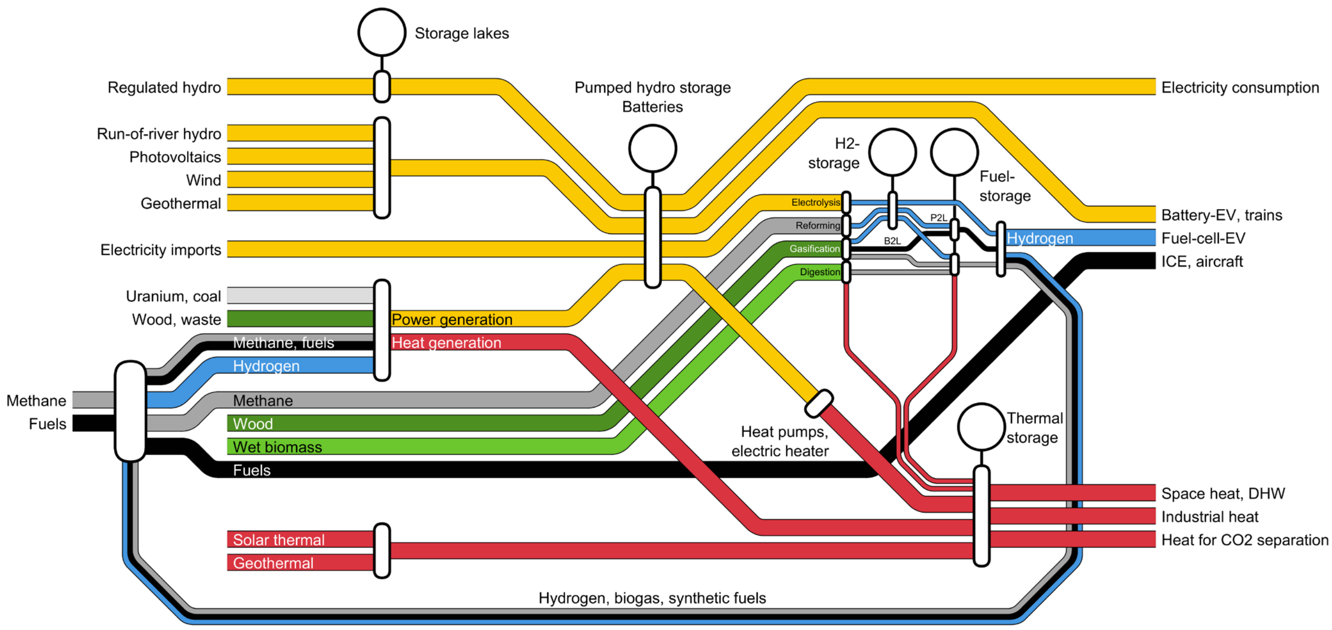
Value of synthetic gases and fuels for the decarbonization of Switzerland (VADER)



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Zusammenfassung

Das Projekt nutzte ein Energiesystemmodell, um den Wert synthetischer Gase und Brennstoffe für die Erreichung der Schweizer Klimaziele zu quantifizieren. Diese sind definiert als Netto-Null-Treibhausgasemissionen im Jahr 2050. Im Gegensatz zu früheren Studien werden auch die Emissionen aus dem Flugverkehr berücksichtigt. Ausgehend vom Szenario CROSS-V2022-01 werden Basisszenarien erstellt. Zusätzlich werden verschiedene Varianten analysiert, welche die Auswirkungen von Importpreisen für Methan, Kerosin und Elektrizität, die Verfügbarkeit einer schweizerischen CO_2-Transportinfrastruktur und die Verfügbarkeit von technologischen Optionen wie auf Vergasung basierende Biomasse-Konversionsprozesse oder eine höhere Kerosinselektivität einer Fischer-Tropsch-Kraftstoffsynthese berücksichtigen. Die Unsicherheit von Schlüsselfaktoren wie Bevölkerungszahl, Nutzenergiebedarf und Technologiekosten wurde durch eine systematische Wiederholung der Analyse mit Hilfe eines Monte-Carlo-Ansatzes berücksichtigt. Die Auswirkungen der Technologieakzeptanz (neue Wasserkraftwerke, mehr Windenergie usw.) wurden untersucht, indem ein innovatives und konservatives Szenario definiert wurde. Aus dieser Analyse lassen sich eine Reihe von Schlussfolgerungen ziehen, die gegenüber künftigen Unwägbarkeiten robust sind.

In den Basisszenarien werden die Netto-Null-Klimaziele mit einem Maßnahmenmix erreicht, der eine Elektrifizierung des Wärme- und Mobilitätssektors und ein starkes Wachstum der Photovoltaik beinhaltet. Die Stromerzeugung wird im Winter durch Gaskraftwerke mit fossilem Methan sichergestellt. Die CO_2-Abscheidung und -Speicherung (CCS) wird eingesetzt, um Emissionen aus Punkt-Quellen wie Müllverbrennungsanlagen, Zementwerken und gas- und holzbefeuerten Heizkraftwerken zu vermeiden, wodurch ebenfalls negative Emissionen entstehen. Zusätzliche negative Emissionen werden mit Hilfe von Direct Air Capture erreicht. In der Luftfahrt wird nach wie vor fossiles Kerosin verwendet, wobei die CO_2-Emissionen durch die oben genannten negativen Emissionen kompensiert werden. Dieses Bild ändert sich, wenn man davon ausgeht, dass die Importpreise für fossiles Methan und Kerosin steigen. Ein dreifacher Anstieg reduziert die Methaneinfuhren auf null. Dies wird durch verschiedene Maßnahmen innerhalb des gesamten Energiesystems ausgeglichen, wobei die wichtigsten der Ausbau der Photovoltaik und die Steigerung der Wasserstoff-Elektrolyse sind. Die Emissionen aus dem Luftverkehr werden weiterhin durch negative Emissionen kompensiert. Im Extremfall, in dem keine fossilen Brennstoffe importiert werden, wird Kerosin im Inland über ein Power-to-Liquid-Verfahren hergestellt, was einen massiven Ausbau der Photovoltaik und der Elektrolyse erfordert. Dies führt zu einem starken Anstieg der Gesamtsystemkosten.

In den Basisszenarien wurde davon ausgegangen, dass keine Stromimporte (vor allem im Winter) und keine auf Vergasung basierenden Biomasseumwandlungsprozesse stattfinden. Die grundlegenden Schlussfolgerungen ändern sich jedoch nicht, wenn diese Beschränkungen aufgehoben werden: Wenn die Importpreise für Methan und Kerosin erhöht werden, gehen die Methanimporte zunächst schnell zurück und werden durch mehr Photovoltaik und Elektrolyse ersetzt, während die Emissionen des Luftverkehrs weiterhin durch negative Emissionen kompensiert werden. Wenn Importe verboten werden, wird Kerosin über Power-to-Liquid-Verfahren synthetisiert, wobei der einzige Unterschied im Anteil des importierten Stroms gegenüber dem durch Photovoltaik erzeugten Strom besteht. Vergasungsbasierte Biomassekonversionsverfahren sind ein wertvolles Element im Technologiemix, ihre Wirkung ist jedoch durch die Verfügbarkeit von Biomasse begrenzt. Das Fehlen einer schweizerischen CO_2-Transportinfrastruktur erfordert mehr Kompensationen durch negative Emissionen im Ausland, was zu höheren Gesamtsystemkosten führt.

Wenn die Emissionen aus dem Flugverkehr durch negative Emissionen kompensiert werden, ergeben sich die effektiven Versorgungskosten von Kerosin aus der Summe der Importkosten und der Kompensationskosten. Solange diese unter dem Preis von Sustainable Aviation Fuels (SAF) liegen, scheint die Kompensation die beste Strategie für die Schweiz zu sein. Wenn Kerosinimporte verboten werden, sind die inländischen Produktionskosten wahrscheinlich höher als die zukünftigen Kosten für SAF auf Basis von Power-to-Liquid. Der Grund dafür ist, dass die wichtigste zusätzliche erneuerbare Stromquelle in der Schweiz die Photovoltaik ist, die nur geringe jährliche Volllaststunden aufweist, was

negative wirtschaftliche Auswirkungen auf die weiteren Verarbeitungsschritte hat, nämlich die Elektrolyse und die Kraftstoffsynthese.

In der Analyse, die in diesem Projekt durchgeführt wurde, wurde die Luftfahrt als der Teil des Energiesystems betrachtet, der am schwierigsten zu dekarbonisieren ist. Langfristig wird dies die Synthese von Flugtreibstoffen erfordern, und Power-to-Liquid scheint die Technologie der Wahl zu sein. Die Schweiz sollte sich aktiv in der Forschung, Entwicklung, Demonstration und Kommerzialisierung dieser Technologien engagieren, nicht um eine inländische Produktion aufzubauen, sondern um Partner in einer internationalen Allianz zu werden und die Versorgung mit solchen Treibstoffen in Zukunft zu sichern.

Résumé

Le projet a utilisé un modèle de système énergétique pour quantifier la valeur des gaz et des carburants synthétiques pour atteindre les objectifs climatiques de la Suisse. Ceux-ci sont définis comme des émissions nettes de gaz à effet de serre nulles en 2050. Contrairement aux études précédentes, nous incluons également les émissions de l'aviation. Des scénarios de base sont construits, en partant de la définition de CROSS-V2022-01. En outre, plusieurs variantes sont analysées qui explorent l'effet des prix d'importation du méthane, du kérosène et de l'électricité, la disponibilité d'une infrastructure suisse de transport du CO_2 et la disponibilité d'options technologiques telles que les processus de conversion de la biomasse basés sur la gazéification ou une sélectivité plus élevée du kérosène dans une synthèse de carburant Fischer-Tropsch. L'incertitude des facteurs clés tels que le nombre d'habitants, la demande d'énergie utile et les coûts technologiques a été prise en compte en répétant l'analyse de manière systématique à l'aide d'une approche Monte Carlo. L'effet de l'acceptation des technologies (nouvelles centrales hydroélectriques, plus d'énergie éolienne, etc.) a été étudié en définissant un scénario innovant par rapport à un scénario conservateur. Un certain nombre de conclusions peuvent être tirées de cette analyse qui est robuste en ce qui concerne les incertitudes futures.

Dans les scénarios de base, les objectifs climatiques nets zéro sont atteints grâce à un ensemble de mesures comprenant une électrification du secteur du chauffage et de la mobilité et une forte croissance du photovoltaïque. La production d'électricité est assurée en hiver par des centrales à gaz utilisant du méthane fossile. Le captage et le stockage du CO_2 (CSC) sont utilisés pour éviter les émissions provenant de sources ponctuelles telles que les usines de valorisation énergétique des déchets, les cimenteries et les centrales de cogénération gaz/bois, générant également des émissions négatives. Des émissions négatives supplémentaires sont obtenues grâce au captage direct dans l'air. L'aviation utilise toujours du kérosène fossile, les émissions de CO_2 étant compensées par les émissions négatives susmentionnées. La situation change lorsque l'on suppose que les prix à l'importation du méthane et du kérosène fossiles augmentent. Une multiplication par trois réduit les importations de méthane à zéro. Cette situation est compensée par plusieurs mesures dans l'ensemble du système énergétique, les plus importantes étant l'augmentation de la production photovoltaïque et l'augmentation de l'électrolyse de l'hydrogène. Les émissions de l'aviation sont encore compensées par des émissions négatives. Dans le cas extrême où il n'y aurait pas d'importations de produits fossiles, le kérosène serait produit dans le pays par un processus de conversion de l'énergie en liquide, ce qui nécessiterait une augmentation massive de la production photovoltaïque et de l'électrolyse. Cela conduit à une forte augmentation des coûts totaux du système.

Les scénarios de base supposaient l'absence d'importations d'électricité (principalement en hiver) et de processus de conversion de la biomasse par gazéification. Toutefois, le scénario de base ne change pas si ces restrictions sont supprimées : lorsque les prix d'importation du méthane et du kérosène sont augmentés, les premières importations de méthane chutent rapidement et sont remplacées par davantage de photovoltaïque et d'électrolyse, tandis que l'aviation reste décarbonisée par des

émissions négatives. Lorsque les importations sont interdites, le kérosène est synthétisé par des procédés de conversion de l'énergie en liquide, la seule différence étant la part de l'électricité importée par rapport à l'électricité produite par le photovoltaïque. Les procédés de conversion de la biomasse par gazéification sont un élément précieux du mix technologique, mais leur impact est limité par la disponibilité de la biomasse. L'absence d'une infrastructure suisse de transport de CO_2 nécessite davantage de compensations par des émissions négatives à l'étranger, ce qui entraîne une augmentation des coûts totaux du système.

Lorsque les émissions de l'aviation sont compensées par des émissions négatives, les coûts d'approvisionnement effectifs du kérosène sont la somme des coûts d'importation et des coûts de compensation. Tant que ces derniers sont inférieurs au prix des carburants d'aviation durables (SAF), la compensation semble être la meilleure stratégie pour la Suisse. Lorsque les importations de kérosène sont interdites, les coûts de production nationaux sont probablement plus élevés que les futurs coûts des SAF basés sur l'énergie liquide. La raison en est que la principale source d'électricité renouvelable supplémentaire en Suisse est le photovoltaïque qui a peu d'heures de pleine charge annuelle, ce qui a des conséquences économiques négatives sur les étapes de traitement ultérieures, à savoir l'électrolyse et la synthèse du carburant.

L'analyse effectuée dans le cadre de ce projet a considéré l'aviation comme la partie du système énergétique la plus difficile à décarboniser. À long terme, cela nécessitera la synthèse des carburants d'aviation et la conversion de l'énergie en liquide semble être la technologie de choix. La Suisse devrait s'engager activement dans la recherche, le développement, la démonstration et la commercialisation de ces technologies, non pas pour construire une production nationale mais pour devenir partenaire d'une alliance internationale et pour garantir l'approvisionnement de ces carburants à l'avenir.

Summary

The project used an energy system model to quantify the value of synthetic gases and fuels for reaching the Swiss climate goals. These are defined as net-zero greenhouse gas emissions in 2050. In contrast to previous studies, we include also emissions from aviation. Basic scenarios are built, starting from the CROSS-V2022-01 scenario. In addition, several variants are analysed which explore the effect of import prices for methane, kerosene and electricity, the availability of a Swiss CO_2 transport infrastructure and the availability of technological options such as gasification-based biomass conversion processes or a higher kerosene selectivity of a Fischer-Tropsch fuel synthesis. The uncertainty of key drivers such as population count, useful energy demand and technology costs was considered by repeating the analysis in a systematic way using a Monte Carlo approach. The effect of technology acceptance (new hydro power plants, more wind energy, etc) was studied by defining an innovative vs. a conservative scenario. A number of conclusions can be drawn from this analysis which are robust with regards to future uncertainties.

In the basic scenarios the net-zero climate goals are achieved with a mix of measures including an electrification of the heating and mobility sector and a strong growth of photovoltaics. Electricity generation is secured in winter by gas power plants using fossil methane. CO_2 capture and storage (CCS) is used to avoid emissions from points sources such as waste-to-energy plants, cement plants and gas/wood fired combined heat and power plants, generating also negative emissions. Additional negative emissions are achieved with the help of direct air capture. Aviation still uses fossil kerosene with the CO_2 emissions being compensated by the aforementioned negative emissions. This picture changes when import prices for fossil methane and kerosene are assumed to rise. A three-fold increase reduces methane imports to zero. This is balanced by several measures within the whole energy system, the most important being more photovoltaic generation and an increase of hydrogen electrolysis. Emissions from aviation are still compensated with negative emissions. In the extreme case of no fossil

imports, kerosene is produced domestically via a power-to-liquid process, requiring a massive increase of photovoltaics and electrolysis. This leads to a strong increase of total system costs.

The basic scenarios assumed no electricity imports (mostly in winter) and no gasification-based biomass conversion processes. However, the basic storyline does not change if these restrictions are removed: when import prices for methane and kerosene are increased, first methane imports drop quickly and are replaced by more photovoltaics and electrolysis, while aviation is still decarbonized by negative emissions. When imports are banned, kerosene in synthesized via power-to-liquid processes, the only difference being the share of imported electricity vs. electricity produced by photovoltaics. Gasification-based biomass conversion processes are a valuable element in the technology mix, however, their impact is limited by the availability of biomass. Not having a Swiss CO_2 transport infrastructure requires more compensations by negative emissions abroad, leading to higher total system costs.

When emissions from aviation are compensated by negative emissions, the effective supply costs of kerosene are the sum of import costs and compensation costs. As long as these are below the price of Sustainable Aviation Fuels (SAF), compensation appears to be the best strategy for Switzerland. When kerosene imports are banned, the domestic production costs are likely higher than future power-to-liquid based SAF costs. The reason is that the main additional renewable electricity source in Switzerland is photovoltaics that has low annual full load hours with negative economic consequences on the further processing steps, namely electrolysis and fuel synthesis.

The analysis done in this project included aviation as the part of the energy system that is hardest to decarbonize. In the long run this will require the synthesis of aviation fuels and power-to-liquid seems to be the technology of choice. Switzerland should actively engage in research, development, demonstration and commercialization of these technologies, not build up a domestic production but to become a partner in an international alliance and to secure the supply of such fuels in the future.

Contents

Abbreviations

B2G	Biomass gasification to methane
B2H2	Biomass gasification to hydrogen
B2L	Biomass gasification to liquid fuels
B2X	Biomass to X, thermochemical conversion of biomass
BECCS	Bioenergy with CCS
BEV	Battery electric vehicle
CCS	Carbon Capture & Storage
CCU	Carbon Capture & Utilization
CHP	Combined Heat & Power
DAC	Direct Air Capture
DACCS	Direct Air Capture with CCS
DHN	District heating networks
FCEV	Fuel cell electric vehicle
FT	Fischer-Tropsch synthesis, technology to produce liquid fuels from syngas
P2G	Power to methane; electrolysis with subsequent methanation using CO_2
P2H2	Power to hydrogen, electrolysis
P2L	Power to liquid; electrolysis with subsequent FT-synthesis using CO_2
P2X	Power to X, conversion of electricity to some chemical energy carrier
SAF	Sustainable aviation fuels
SMR	Steam methane reforming
WGS	Water-gas-shift reaction
RWGS	Reversed water-gas-shift reaction

“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.”

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

1 Introduction

1.1 Background information and current situation

Historically, energy has been the dominant part of the Swiss greenhouse emissions (Figure 1) to supply the country's needs for electricity, heat and mobility. Today these needs are satisfied, to a large extent, by hydropower, nuclear electricity and by imported fossil fuels like oil and gas. By 2050, the country aims at reaching net-zero GHG emissions. Since some emissions (agriculture, industry and aviation) can hardly be avoided, the energy system will have to turn from a net emitter to a net sink.

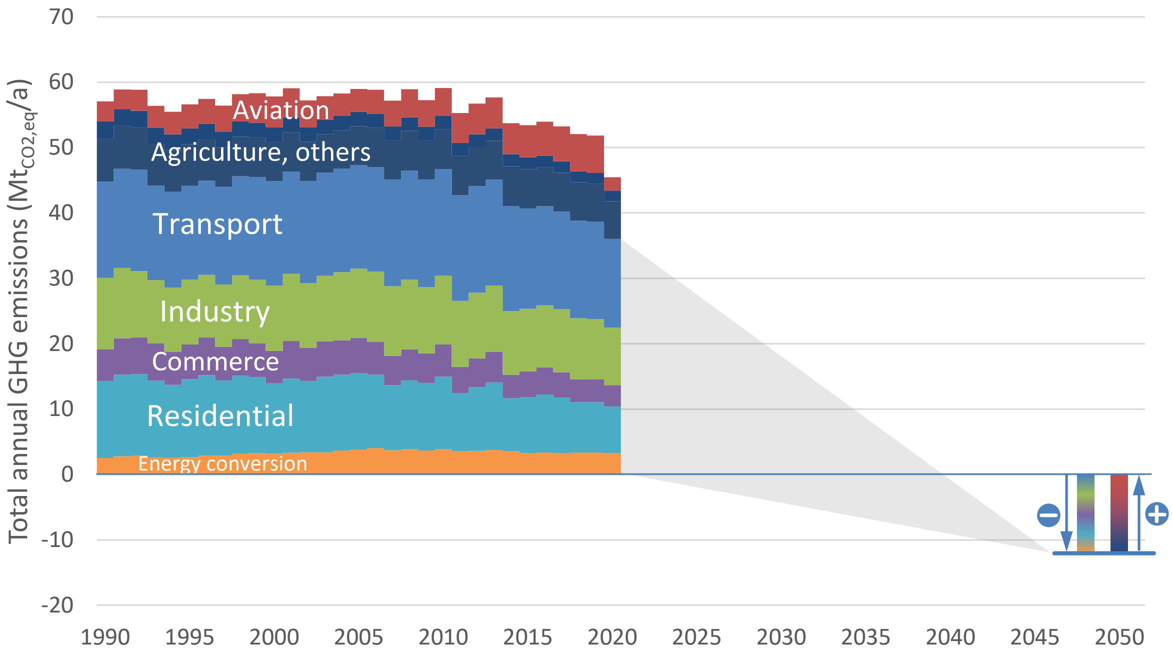

Figure 1: Historical GHG emissions and net-zero target [26].

1.2 Purpose and objectives of the project

While the electrification of the energy system will clearly play the major role for reaching the net-zero target, the question that is still open is what type of chemical, non-fossil energy carriers will be needed in the future. The purpose of the present analysis is to give answers to this question.

2 Synthetic gases & fuels

It is well-known that any strategy for decarbonization will heavily rely on the electrification of the demand sectors heat and mobility. This will reduce the primary energy consumption due to the higher efficiency of heat pumps and electric vehicles compared to their fossil-fuel-based counterparts. However, there is an obvious downside of this approach: while fossil chemical energy carriers such as methane, gasoline, diesel or kerosene are commodities that can be easily stored, this is not the case for electricity. A possible solution to this problem is suggested, namely the transformation of electricity into chemical energy carriers, the so-called Power-to-X approach, more precisely Power-to-X-to-Y since the X may just be an intermediate energy form that is later transformed into the final product Y. Note that we follow the common practice and refer to liquid chemical energy carriers (diesel, kerosene, etc) as fuels, and to gaseous chemical energy carriers (hydrogen, methane) as gases.

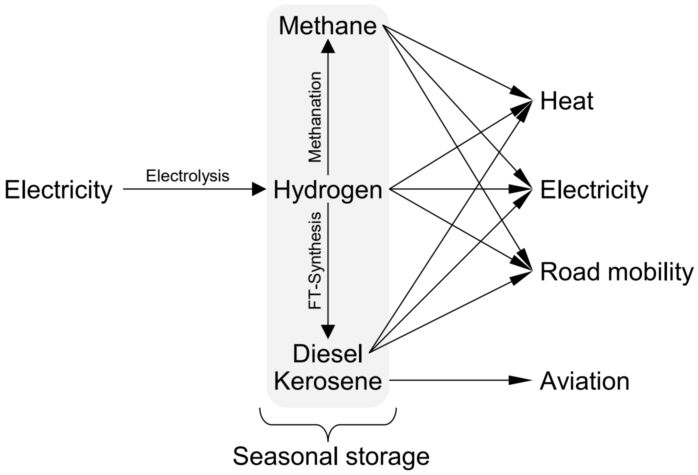

Figure 2: Power-to-X-to-Y options.

Figure 2 illustrates the various options. Starting point is generally the production of hydrogen through electrolysis. With the addition of CO_2, this hydrogen may be further transformed into methane or into fuels such as Diesel or kerosene. The reason for doing this can be twofold: (1) it is easier and cheaper to transport and store a liquid fuel, and (2) some applications such as aviation can (so far) only work with fuels.

While we put the three types of chemical energy carriers in the focus of the present study, it must be recognized that Power-to-X is only one option to produce these substances:

- Hydrogen may be produced from electrolysis, steam methane reforming (SMR) or biomass gasification. We do not consider hydrogen imports.
- Methane may be synthesized from hydrogen and CO_2 (methanation), it can come from anaerobic digestion, biomass gasification or it can be imported as fossil natural gas.
- Kerosene and Diesel (70%/30% fraction) may be synthesized from hydrogen and CO_2 (reversed water-gas-shift (RWGS) reaction and Fischer-Tropsch synthesis), it can alternatively be produced directly from biomass (gasification and Fischer-Tropsch synthesis) or it can be imported as fossil kerosene and Diesel.

All these options are the result of a technical production process, therefore we term the resulting chemical energy carriers as synthetic gases & fuels, in contrast to chemical energy carriers that result directly from fossil resources (we neglect the fact than gasoline, diesel and kerosene are of course not natural substances but themselves a result of crude oil processing).

To understand the structure of the subsequent result chapter we form two groups of synthetic gases & fuels:

- Synthetic electric gases & fuels (P2X) are hydrogen from electrolysis, methane from methanation (a synthesis of H2 and CO_2 via the Sabatier process) and kerosene/Diesel from a power-to-liquid process (a synthesis of H2 and CO_2 via the Fischer-Tropsch process).
- Synthetic biological gases & fuels (B2X) result from biomass gasification where the resulting syngas (mixture of mainly H2 and CO) is further processed to deliver hydrogen, methane or kerosene/Diesel.

Note that established processes such as SMR (CH4 → H2) and anaerobic digestion (biomass → CH4) are considered standard and always present in all scenarios. The P2X and B2X routes have strong commonalities, the main difference is that P2X usually starts with electrolyzed hydrogen and CO_2 that is transformed into a syngas by a RWGS reaction, while biomass gasification directly produces a syngas, where a WGS reaction is used to properly tune the H2/CO ratio. In reality the two routes can be tightly combined, for instance by using the CO_2 that will always result from a biomass gasification and combining it with electrolyzed H2 to form more syngas and its subsequent products. In a nutshell, P2X processes start with electricity and captured CO_2, whereas B2X processes start with biomass that provide biogenic CO_2, and can therefore result in negative emissions.

We consider that any process that generates synthetic kerosene will inevitably produce a fraction of Diesel. This fuel may be used in the model for mobility, residential heating, industrial process heat or as a replacement fuel in gas turbine power plants. At least in the latter case a CO_2 separation is in principle possible. The analysis will show whether this extra Diesel generation is actually an advantage or a disadvantage. Table 1 summarizes the different production pathways and the possible use cases of the energy carriers. Note that the project proposal had considered methanol as an additional synthetic fuel. Due to the limited technical detail that a model like SES-ETH can provide, there is actually no difference between methanol and the other synthetic fuels Diesel and kerosene. Any statement that will be made on the value of producing such fuels is therefore equally applicable to methanol.

The analysis presented in the following sections shall show under which circumstances synthetic gases & fuels of various production routes appear within the cost-optimal energy system configuration for a net-zero scenario. Since synthetic methane and kerosene require CO_2, this analysis will also give an answer to the question of CO_2-Capture & Utilization (CCU) vs. CO_2-Capture & Storage (CCS).

Table 1: Production pathways and uses of synthetic gases & fuels.

Production process	Energy carrier	SFH/MFH heating	CHP in DHN	CHP in industry	Waste-to-energy hubs	Cement plants	Thermal power plants	Road mobility	Aviation
Electrolysis Steam methane reforming Biomass gasification + WGS	Hydrogen			X	X	X	X	X	
Anaerobic digestion RWGS + methanation Biomass gasification + methanation	Methane	X	X	X	X	X	X	X	
RWGS + FT-synthesis Biomass gasification + FT-synthesis	30% Diesel	X	X	X	X	X	X	X	
	70% Kerosene								X
CO_2 separation possible?			X	X	X	X	X		

3 Model and methodology

3.1 Swiss Energyscope Model

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 3). 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]. <u>Note that all inputs and results in this report refer to the target year 2050</u>.

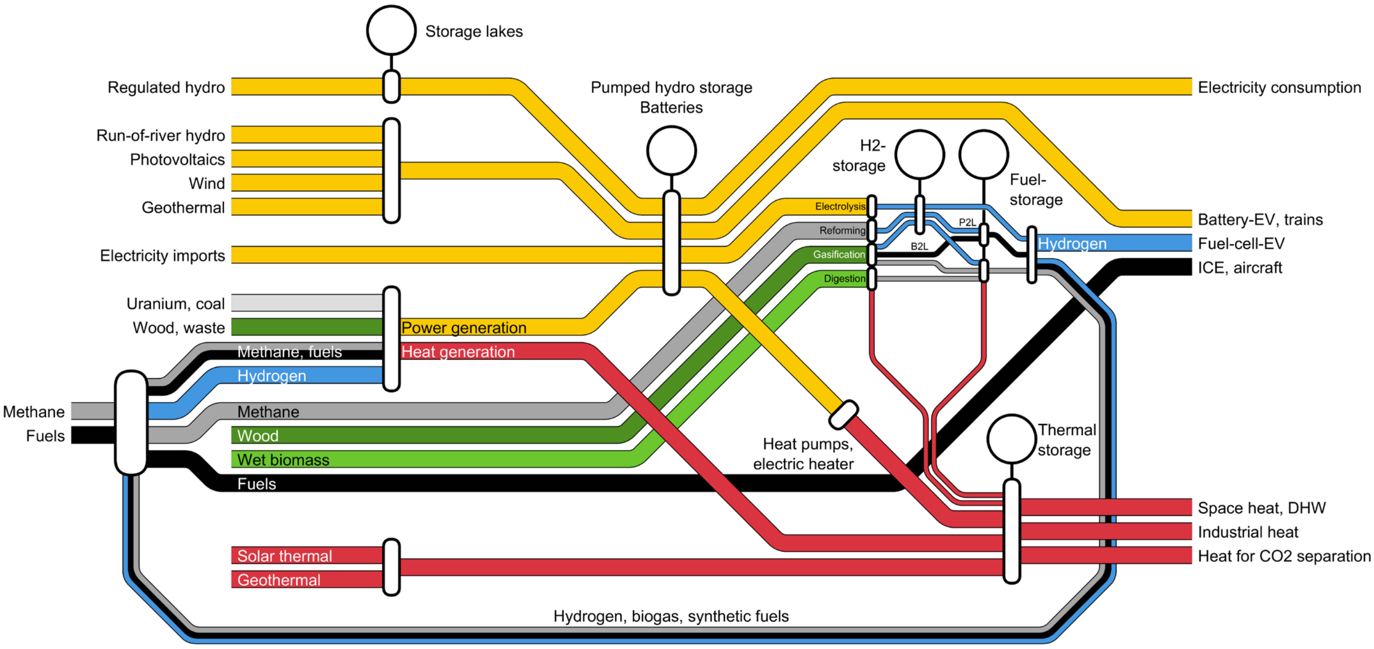

Figure 3: Symbolic representation of the energy system as modelled in SES-ETH.

It is very important to point out the boundaries of the model and the analysis presented in this report. We consider the Swiss energy system in detail, using especially demand projections and the specific resource potential of Switzerland [3]. The latter relates to the hydropower generation (and the possible effect of climate change); and to photovoltaics and wind power, which have relatively low annual full load hours due to the Swiss latitude and continental climate. Additionally, we consider realistic estimates on domestic biomass availability [5]. Any statement that will be made later on production costs of synthetic gases and fuels relates always to these specific Swiss conditions.

3.2 Scenario definition

Our scenarios are based on the CROSS-V2022-01 scenarios [27]. The CROSS scenarios are defined in two dimensions: climate policy and integration with the EU energy market (see Figure 4). We add a third dimension concerning technology development.

3.2.1 Climate policy dimension

The CROSS scenarios include the net zero GHG goal of the Swiss Federal Council. This goal considers 5.9 Mt/a emissions from industry, agriculture and waste disposal in landfills that are difficult to avoid and therefore need to be compensated by negative emissions in other energy sectors or by Direct Air Capture (DAC). In SES-ETH we model these emissions by adding them into the Swiss CO_2 balance. For the present report we go beyond the work done in the Energieperspektiven 2050+ and in the JASM project by considering also the emissions from international aviation. Here we assume a demand for aviation fuels of 25 TWh/a (a slight increase compared to the pre-Covid19 22 TWh/a [9]). This results in 25 TWh/a x 0.265 t_{CO2}/MWh = 6.6 Mt_{CO2}/a. Note that these emissions cannot be avoided at the aircraft, however, the model foresees the option to generate synthetic aviation fuels by Power-to-liquid and Biomass-to-liquid processes, or to compensate by additional negative emissions.

In this study we run the model repeatedly for varying CO_2 targets ranging from +25 Mt/a down to -5 Mt/a. 0 Mt/a would be a “true” net zero scenario, including emissions difficult to avoid and aviation, and without compensating by negative emissions abroad (CROSS: **Domestic-**). Making such a sweep of CO_2 targets gives a more complete picture of the technologies that become part or stop being part of the optimal system when approaching the net-zero target. Moreover, by doing this sweep over various CO_2 targets, we also include the CROSS variant with compensation abroad (CROSS: **Abroad-**), which corresponds to the 5.9 Mt/a target in our scenario setup.

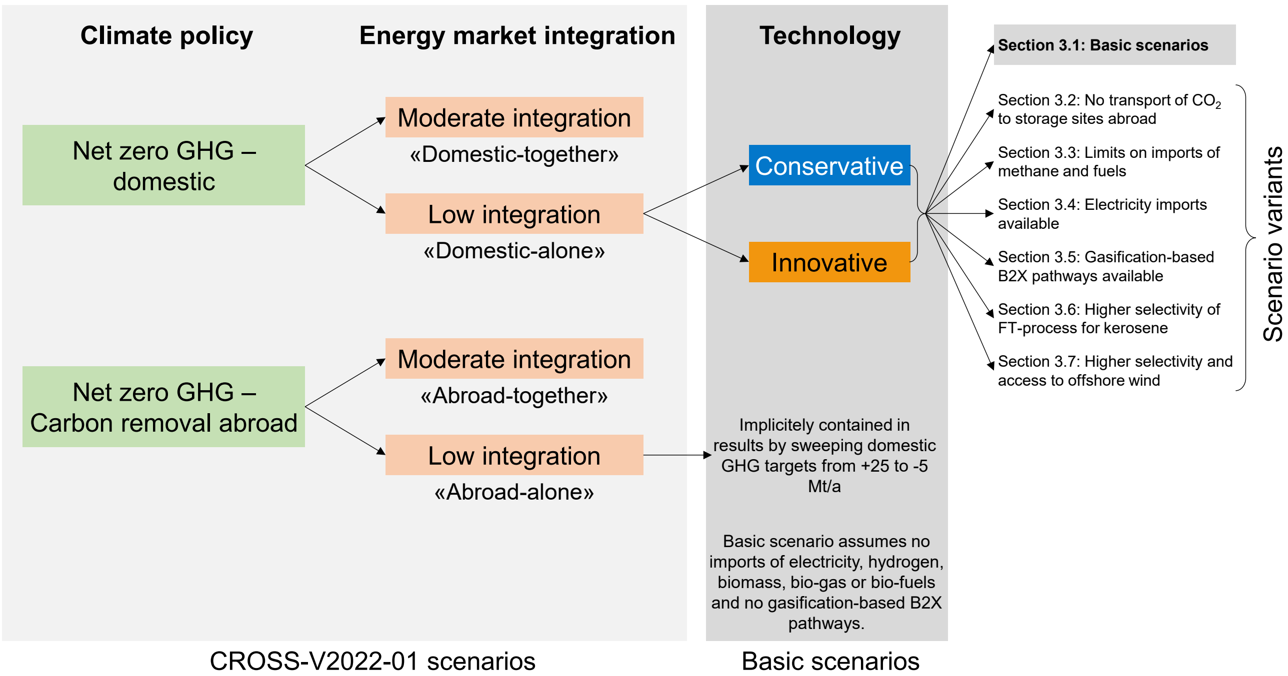

Figure 4: CROSS-V2022-01 scenarios and application to the present study [27].

3.2.2 Energy market integration dimension

The second dimension in the CROSS scenarios is the dimension concerning energy market integration, with low and high integration with Europe. In SES-ETH, we do not explicitly model the surrounding countries. We model imports of energy carriers such as electricity and fossil gases and fuels (methane, gasoline, diesel, kerosene) assuming a price and an unlimited availability. We do not consider the imports of raw biomass (e.g., wood) and chemical energy carriers that have been produced using biological and/or thermochemical pathways (see Section 2 on synthetic gases & fuels). Instead, we determine the supply costs of such gases and fuels in Switzerland and can, therefore, deduce a price estimate below which an import would be preferable to a domestic production.

CROSS scenarios include two variants for the second dimension, namely moderate and low integration. Our assumptions correspond to the low integration variant. They differ in the treatment of electricity imports, where the basic scenario has no imports, and scenario variants consider unlimited imports at varying prices. In summary, we cover the CROSS scenarios **Domestic-alone** and **Abroad-alone**.

3.2.3 Technological dimension

We added an additional dimension to the CROSS scenarios to model technology deployment. This dimension has two alternatives and forms two basic scenarios: **Innovative** and **Conservative**. As shown in Table 2 these differ in terms of renewable potential and the availability of certain technologies. The assumptions concerning biomass technologies require some additional explanation:

- Centralized processing of manure: Nowadays, manure is used in small CHP engines in the farms where it is produced. We assume in the innovative variant that an infrastructure to transport manure from farms to large scale facilities is established. This allows to feed bio-methane to the gas network.
- In the innovative variant, we assume that centralized units for pyrolysis or hydro-thermal carbonisation (HTC) of digestate (from anaerobic digestion of manure or green waste) are available. These centralized units process the digestate and fix the carbon in a way that it is less attacked by microorganisms. This allows to create negative emissions without the need of transporting and storing CO_2.
- The last biomass technology in the innovative scenario is the connection of a centralized anaerobic digestion facility to a CO_2 network, either directly to a pipeline, e.g., by locating such a facility close to a waste-to-energy plant, or via road or rail transport.

Table 2: Technology dimensions of the basic scenarios.

	Conservative	Innovative
Total hydropower potential	< 33.6 TWh/a	< 37.1 TWh/a
Reservoir volume	< 6.5 TWh	< 8.5 TWh
Wind power	< 0.9 GW	< 2.1 GW
Wood potential	15-16 TWh/a	19-20 TWh/a
Alpine photovoltaics	No	< 4 GW
Centralized processing of manure	No	Yes
Centralized pyrolysis/HTC of digestate	No	Yes
Connection of anaerobic digestion facility to CO_2 network	No	Yes
Seasonal hydrogen storage in caverns (in CH)	No	Yes
Seasonal thermal storage	No	Yes
Deep geothermal energy	No	< 10 TWh/a

3.3 Model inputs and assumptions for basic scenarios

A large number of input data and assumptions enter an energy system model such as SES-ETH. In this subsection we list the most important ones:

- The target year for the analysis is 2050. All assumptions listed in this section refer to this year.
- The development of population and gross domestic product is taken from the BFS. We use a low, reference and high scenario (see Table 3).
- Energy demand is expressed in terms of useful energy demand, not as final energy demand. Assumptions concerning useful energy demand are listed in Table 3. The values are proportional to population and/or GDP and show a variation, accordingly.
- The resource potential for different types of biomass and waste is also listed in Table 3. Some numbers scale with the population and/or GDP and are given as a range.
- Investment costs are annualized using the lifetime and a weighted average cost of capital of 2.5%. Annual fixed operation & maintenance costs are assumed to be 3% of the investment costs. Variable operation & maintenance costs are set to zero. Investment costs and energy conversion efficiencies are listed in Table 4. In case of chemical energy, efficiency refers always to the lower heating value.
- For the basic scenarios we consider no electricity imports and no gasification-based B2X production pathways. The reason is to highlight the possible role of P2X pathways, for instance as seasonal storage options. Both restrictions are later released in scenario variants.
- Import costs of energy carriers are listed in Table 3.
- The costs for CO_2 export consider everything from the Swiss border to the final storage site (see Table 3). Costs for CO_2 separation in Switzerland are considered separately as domestic technologies (see Table 2). The basic scenarios assume that a domestic CO_2 transport infrastructure exists that collects CO_2 captured from point sources within Switzerland, and is connected to a European CO_2 transport infrastructure with access to storage sites abroad.
- As usual, the demand for mobility services is expressed in terms of person-kilometers (PKM) and ton-kilometers (TKM) (see [3] for the total amounts and the modal split). Battery-electric vehicles are considered as an option for private cars, buses and road-based freight transport. Here we assume a maximum electric share in terms of PKM and TKM of 100%, 50% and 50%, respectively. The non-electric portion has to be supplied by a liquid or gaseous chemical energy carrier. This assumption is important because it implies a certain base demand for hydrogen (or any other sustainable fuel).
- The demand for space heat and domestic hot water can be satisfied by a large array of technologies [4]. It is clear that district heating networks will have a growing importance and that heat pumps will be the dominating technology for single and multi-family houses, however, without a detailed model of the Swiss housing stock we need to introduce limiting assumptions: Here we assume that at most 30% of the heat demand can be satisfied via district heating networks (fed by waste-to-energy plants, wood CHP plants, geothermal, large scale heat pumps, etc.). For single and multi-family houses, at most 70% of the heat demand can come from heat pumps, the rest has to come from oil, gas or wood. This considers the fact that even in 2050 not every building will be suited for heat pumps. Finally, we assume that from these 70% at most 50% can come from air-source heat pumps. The limit here is noise emissions.
- We use the copper-plate assumption for the electricity grid, only a general grid loss of 7% is considered.

- No such assumption can be done for heating or mobility technologies, since energy cannot be exchanged between separate technologies. Therefore, the end use demand in heating and mobility is split into a number of archetypes (e.g., gas boiler, air-source heat pump, wood boiler for heating; battery-electric vehicle, gasoline vehicle for mobility). The share of the archetypes is an optimization variable.
- Mobility technologies such as battery-electric, fuel-cell-electric or Diesel/gasoline vehicles are not listed since we assume that the costs will have equalized long before 2050.

Several entries in Table 3 and Table 4 show a range of values, acknowledging the uncertainty of these input parameters. We consider this uncertainty by performing a Monte Carlo analysis using Sobol sequences. All results presented in the subsequent sections are therefore presented in terms of statistical distributions.

A note of caution has to be added especially to the investment cost estimates in Table 4. These show usually a considerable scatter which is often due to incoherent assumptions on the scope (e.g., only equipment or also use of land). Tools like SES-ETH minimize the total system costs, i.e., the sum of annualized investment costs, operation & maintenance costs and resource costs. Therefore, investment costs have an impact on the results but often only on the total level of costs, not on the structure of the optimal net-zero energy system and therefore on the broad conclusions that can be drawn.

Table 3: Assumptions on population, GDP, useful energy demand, resource availability and import/export costs [3].

Description	Unit	Range		
Population	Mp	9.54	-	12.10
Gross domestic product	bCHF/a	985	-	1273
Useful energy demand				
Base electricity (households)	GWh/a	10331	-	13109
Base electricity (service)	GWh/a	11759	-	15198
Base electricity (industry)	GWh/a	11499	-	14862
High temperature process heat (industry)	GWh/a	5273	-	6816
Medium teperature process heat (industry)	GWh/a	12305	-	15903
Medium teperature process heat (services)	GWh/a	260	-	335
Space heat SFH (old)	GWh/a	12998	-	14576
Space heat SFH (new)	GWh/a	1049	-	2242
Space heat MFH (old)	GWh/a	14425	-	16176
Space heat MFH (new)	GWh/a	2645	-	5591
Space heat service	GWh/a	13576	-	16871
Space heat industry	GWh/a	2431	-	2975
Domestic hot water (households)	GWh/a	6999	-	8880
Domestic hot water (industry)	GWh/a	582	-	752
Domestic hot water (service)	GWh/a	2452	-	3111
Private cars	Mpkm/a	106924	-	132521
Private motorcycles	Mpkm/a	2357	-	2922
Public tram	Mpkm/a	2121	-	2668
Public bus	Mpkm/a	3473	-	4368
Public train	Mpkm/a	26147	-	32882
Rail transport freight	Mtkm/a	14737	-	18533
Road transport freight	Mtkm/a	23547	-	29504
Resource availability				
Wood (low)	GWh/a	14995	-	16155
Wood (reference)	GWh/a	16742	-	17901
Wood (high)	GWh/a	18710	-	19869
Manure	GWh/a	7318	-	7318
Fresh sewage sludge	GWh/a	1547	-	1963
Wet biomass (e.g. green waste)	GWh/a	3491	-	4232
Municipal and industrial waste	GWh/a	17633	-	22611
Import costs				
Methane	CHF/MWh	30	-	60
Wood	CHF/MWh	40	-	80
Kerosene	CHF/MWh	50	-	100
Diesel	CHF/MWh	50	-	100
Electricity	CHF/MWh	100	-	200
Export costs				
CO_2-storage	CHF/t_{CO2}	100	-	200

Table 4: Assumptions on technology costs and efficiency.

Description	Investment costs	Unit	Lifetime	Energy conversion efficiency (X/Input)				Sources/comments
				Electr.	Thermal	Chem.	Output	
Photovoltaics	500 - 1500	CHF/kW_{el}	25	-	-	-	-	[12]
Alpine photovoltaics	2000	CHF/kW_{el}	25	-	-	-	-	Own estimate
Wind power	2000	CHF/kW_{el}	20	-	-	-	-	[12]
Regulated hydro power	6000	CHF/kW_{el}	40	-	-	-	-	[12]
Run-of-river hydro power	6000	CHF/kW_{el}	40	-	-	-	-	[12]
Pumped hydro storage (only pump)	1000	CHF/kW_{el}	25	-	-	-	-	[12]
Geothermal power plant (incl. well)	10000	CHF/kW_{el}	30	0.125	-	-	-	[12]
Gas turbine combined cycle	400 - 600	CHF/kW_{CH4}	25	0.6	-	-	-	[12]
Gas combined heat & power plant	400 - 600	CHF/kW_{CH4}	25	0.457	0.347	-	-	Personal communication with GE
Biogas combined heat & power plant	6000	CHF/kW_{th}	20	0.33	0.5	-	-	[24]
Small gas CHP plant	400 - 600	CHF/kW_{CH4}	25	0.42	0.43	-	-	[25]
Wood combined heat & power plant	2000 - 3000	CHF/kW_{wood}	25	0.164	0.676	-	-	Own estimate based on [16][17]
Waste combined heat & power plant	2000 - 3000	CHF/kW_{waste}	25	0.119	0.663	-	-	Assumed the same as wood CHP
Industrial gas burner	90	CHF/kW_{th}	25	-	0.7	-	-	[1]
Industrial fuel burner	80	CHF/kW_{th}	25	-	0.7	-	-	[1]
Industrial wood burner	500 - 800	CHF/kW_{th}	25	-	0.8	-	-	[1]
Industrial waste burner	500 - 800	CHF/kW_{th}	25	-	0.75	-	-	[1]
Industrial coal burner	500 - 800	CHF/kW_{th}	25	-	0.8	-	-	[1]
Industrial electric heater	275	CHF/kW_{th}	25	-	0.95	-	-	[1]
Geothermal heat generation	2000 - 4000	CHF/kW_{th}	30	-	1	-	-	Own estimate based on [12]
District heating heat pump	1500 - 2500	CHF/kW_{th}	25	-	4	-	-	Own estimate based on [18][19][20][21]
District heating electrical heater	325	CHF/kW_{th}	25	-	0.95	-	-	Own estimate based on [18][19][20][21]
District heating gas burner	150	CHF/kW_{th}	25	-	0.8	-	-	Own estimate based on [18][19][20][21]
District heating/industrial solar thermal	500 - 750	CHF/kW_{th}	20	-	-	-	-	[22]
Residential air source heat pumps	2000 - 3000	CHF/kW_{th}	25	-	3	-	-	Own estimate based on [18][19][20][21]
Residential water source heat pumps	1200 - 2000	CHF/kW_{th}	25	-	4	-	-	Own estimate based on [18][19][20][21]
Residential ground source heat pumps	4000 - 6000	CHF/kW_{th}	25	-	4	-	-	Own estimate based on [18][19][20][21]
Residential electrical heater	650	CHF/kW_{th}	25	-	0.95	-	-	Own estimate based on [18][19][20][21]
Residential gas boiler	1000	CHF/kW_{th}	25	-	0.8	-	-	Own estimate based on [18][19][20][21]
Residential oil boiler	900	CHF/kW_{th}	25	-	0.8	-	-	Own estimate based on [18][19][20][21]
Residential wood boiler	950	CHF/kW_{th}	25	-	0.8	-	-	Own estimate based on [18][19][20][21]
Residential solar thermal	1200 - 1700	CHF/kW_{th}	25	-	-	-	-	[22]
Electrolysis	600 - 1500	CHF/kW_{H2}	25	-	-	0.7	-	[23]
Methanation process (Sabatier)	1000 - 2000	CHF/kW_{CH4}	25	-	-	0.83	-	Own estimate based on [6][1]
Gasification to methane	2000 - 3000	CHF/kW_{CH4}	25	-	-	0.6	-	[6]
Gasification to hydrogen	3000 - 4000	CHF/kW_{H2}	25	-	-	0.5	-	Own estimate based on [6][1]
Steam methane reforming	1000 - 2000	CHF/kW_{H2}	25	-	-	0.7	-	Own estimate based on [6][1]
Pyrolysis of wood	1200	CHF/kW_{wood}	25	-	-	0.4	-	[7]
Hydrothermal carbonization	1200	$CHF/kW_{biomass}$	25	-	-	0.4	-	Estimated to be similar as pyrolysis
Anaerobic digestion plant	1200	$CHF/kW_{biomass}$	25	-	-	0.36	-	Own estimate
Power-to-liquid (excl. electrolysis)	2500	CHF/kW_{fuel}	25	-	-	0.57	-	Own estimate based on [6][1]
Biomass-to-liquid	3500	CHF/kW_{fuel}	25	-	-	0.4	-	Own estimate based on [6][1]

[1] Estimates on investment costs of thermochemical plants show considerable scatter. Instead of combining a variety of sources that are not comparable we started from a system for biomass conversion to synthetic methane that was thoroughly studied by PSI. We assume that a conversion to hydrogen is slightly more expensive, similarly a conversion to liquid fuels. On the contrary we consider that purely gas-based systems like SMR or methanation are less expensive since they do not have to deal with biomass as a feedstock.

CO_2-separation from flue gas	1800	CHF/(kg$_{CO2}$/h)	25	0.1 kWh$_{el}$/kg	1 kWh$_{el}$/kg	-	-	[10]
Direct air capture	10000	CHF/(kg$_{CO2}$/h)	25	0.4 kWh$_{el}$/kg	2 kWh$_{el}$/kg	-	-	[11]
Residential thermal energy storage	100	CHF/kWh$_{th}$	25	-	-	-	0.9	[13]
Short term large thermal energy storage	10	CHF/kWh$_{th}$	30	-	-	-	0.9	[13]
Seasonal thermal energy storage	0.5 - 1.5	CHF/kWh$_{th}$	30	-	-	-	0.9	[13]
Battery storage	100	CHF/kWh$_{el}$	20	-	-	-	0.8	[14]
Short term hydrogen storage	10 - 20	CHF/kWh$_{H2}$	25	-	-	-	0.9	[15]
Seasonal hydrogen storage	0.5 - 1	CHF/kWh$_{H2}$	25	-	-	-	0.9	[15]
Seasonal methane storage	0.25	CHF/kWh$_{CH4}$	25	-	-	-	0.9	3 times higher energy density than hydrogen
Fuel storage	0.1	CHF/kWh$_{fuel}$	25	-	-	-	1	Own estimate

4 Results and discussion

As stated in the introduction we aim at delivering robust recommendations on the value of synthetic gases & fuels that are as insensitive to our assumptions as possible. To achieve this, we analyse the basic scenarios introduced in Section 3.2 and we construct a series of variants (see also Figure 4):

- Results of the basic scenarios are presented in Section 4.1.
- In Section 4.2 we consider a variant where no Swiss CO_2 transport infrastructure is established, meaning that no CO_2 from Swiss point sources can be transported to storage sites abroad.
- We then consider the effect of increasing the import prices of methane and kerosene/Diesel, or even blocking imports in Section 4.3.
- In Section 4.4 and 4.5 we release the constraints on electricity imports and gasification-based B2X production pathways, respectively.
- In Section 4.6 we consider the question whether increasing the kerosene selectivity of a Fischer-Tropsch process from 70% to 100% would be beneficial.
- Section 4.7 presents the results of a thought experiment, what would happen if Switzerland had access to offshore wind resources.
- Section 4.8 interprets the previous results from the point of view of seasonal storage, giving indications to which extent P2X technologies help to seasonally balance the energy system.
- The last Section 4.9 focus of cost-production curves for hydrogen and kerosene.

4.1 Basic scenarios: no electricity import, no gasification-based B2X

Figure 5 shows results for the two basic scenarios defined in Table 2. It displays several key indicators and their dependence on the overall Swiss GHG emission target (varied from +25 Mt/a down to -5 Mt/a). The Monte Carlo analysis of uncertain inputs (see Section 3.3) results in a statistical distribution that is shown as a box plot with median, inter-quartile range and min/max. The target range around net-zero is highlighted in grey.

The following observations can be made: of the available P2X options, only electrolysis is chosen, however, at a very low level of less than 2 TWh_{H2}/a (Figure 5 (a)). More hydrogen is produced via SMR coupled with CCS, i.e., *blue* hydrogen (not shown). No synthetic methane or Diesel/kerosene is produced via P2X pathways (Figure 5 (b) and (c)). Note that gasification-based B2X pathways are excluded and therefore zero in (d-f). Methane imports (k) are at a similar level as today (30-35 TWh/a [9]), more for **Conservative** than for **Innovative** due to lower levels of hydro power, less wood, absence of geothermal energy, etc. As a consequence, the amount of stored CO_2 is also higher for **Conservative**. All CO_2 that is separated either from point sources such as waste-to-energy, cement, steam reforming, wood and gas CHP plants, or from the atmosphere is stored, cutting fossil unavoidable emissions and partly generating biogenic negative emissions (p).

Models like SES-ETH have the interesting feature that they allow to calculate the marginal cost of any constraint in the model. In this scenario we did not consider the import of CO_2-neutral gases & fuels (e.g., green or blue hydrogen, bio-methane, sustainable aviation fuels, etc). The model now allows to evaluate the benefit of releasing this constraint. This benefit is expressed in CHF/MWh and in can be interpreted as the cost reduction in CHF for the overall system if one MWh of a given CO_2-neutral chemical energy carrier could be imported at zero cost.

Assuming that the CO_2-neutral chemical energy carrier could be imported exactly at this marginal cost, then the effect on the overall energy system costs would be neutral. This means that an import at any price below this marginal cost is beneficial, any import at a cost above is not. Another interpretation is possible: if the marginal cost of importing blue or green hydrogen is say 150 CHF/MWh, then importing 1 MWh of hydrogen at this price avoids the domestic supply of 1 MWh of hydrogen. Since the cost remains the same for the overall energy system, the cost of supplying this 1 MWh domestically is exactly 150 CHF/MWh. The marginal cost is therefore also a measure of the marginal domestic supply cost.

Precisely the same consideration can be made regarding the marginal CO_2 avoidance cost (see Figure 5 (o)). This corresponds to the cost of avoiding another ton of CO_2 and is expressed in terms of CHF/t_{CO2}. We did not model the "import" of CO_2 compensation certificates, which is the exact equivalent to the aforementioned CO_2-neutral chemical energy carriers. If such certificates where available at say 400 CHF/t_{CO2} than an import would be preferable to a domestic solution if the CO_2 avoidance costs is above this value. If it is below, imports are not beneficial and a domestic solution is preferable.

Figure 5 (g-i) shows the supply costs for the aforementioned three energy carriers. For hydrogen (g) this cost is around 150 CHF/MWh in the net-zero target range (grey area). For methane (h) and kerosene (i) it approaches 140 and 200 CHF/MWh, respectively. This seems surprising since the average import prices of methane and kerosene are 45 and 75 CHF/MWh, respectively (see Table 3). However, in a net-zero scenario the fossil emissions of these energy carriers have to be compensated. The marginal CO_2 avoidance costs in the target range are approx. 450 CHF/MWh (Figure 5 (o)). Considering the CO_2 intensity of methane, the costs of providing methane in a net-zero scenario is 45 CHF/MWh + 0.2 t_{CO2}/MWh x 450 CHF/t_{CO2} = 135 CHF/MWh. For kerosene this is 75 CHF/MWh + 0.265 t_{CO2}/MWh x 450 CHF/t_{CO2} = 200 CHF/MWh, the values seen in Figure 5 (h-i).

The CO_2 avoidance cost increases monotonically for reducing CO_2 targets, reaching finally some 400-500 CHF/t_{CO2}. This plateau corresponds to the marginal cost of direct air capture which picks up at CO_2 targets of 5-10 Mt/a (Figure 5 (q)). Below this range, other negative emission technologies are used such as CO_2 separation from anaerobic digestion or wood-CHP plants with CCS (bio-CCS) that have lower CO_2 avoidance costs.

Figure 6 gives a more complete picture of the energy flows for the two basic scenarios. The Sankey diagrams follow the structure of Figure 3 and visualize the range of results by different shades. The numbers indicate the median value. In a nutshell, the differences between **Conservative** and **Innovative** is a lower potential for wood usage and biogas production and the absence of geothermal energy. This is compensated by significantly higher methane imports which in turn necessitate a larger amount of CO_2 separation (Figure 5 (o)). This can be seen indirectly in the higher demand for heat for CO_2 separation at the bottom right of the Sankey diagrams.

The insight from the analysis of the basic scenarios can be summarized like this: the cost-optimal strategy to reach the net-zero range is not to avoid all fossil imports of gases and fuels but to compensate those with all available negative emission technologies. Synthetic electricity based (P2X) gases & fuels play no role. There is a clear cost benefit of the **Innovative** scenario over the **Conservative**.

Figure 5: Results for basic scenarios Innovative and Conservative: no electricity imports and B2X production pathways.

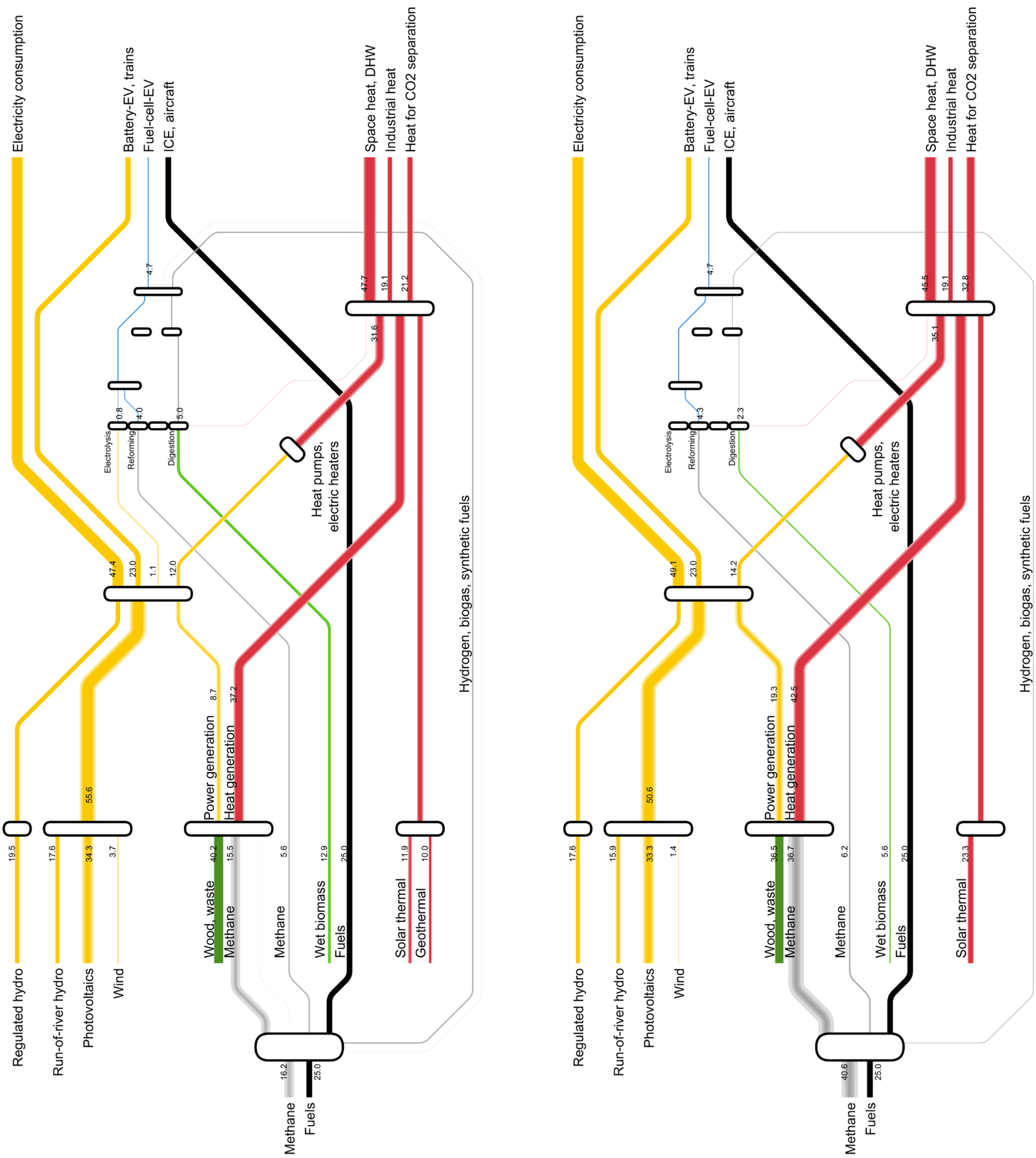

Figure 6: Energy flows in TWh/a for Innovative (left) and Conservative (right) basic scenarios; 0 Mt/a; no electricity imports and B2X production pathways.

4.2 Scenario variants: no CO_2 transport infrastructure in Switzerland

The basic scenarios assume that a Swiss CO_2 transport infrastructure is established that allows to collect CO_2 from Swiss point sources and to transport it to the border where it is then passed to a European CO_2 transport infrastructure with access to storage sites. In this section we consider the case that such a Swiss CO_2 transport infrastructure is not available.

Here we distinguish two distinct types of CO_2 point sources: The first type includes waste-to-energy plants, wood- or gas-fired CHP plants and cement plants located in Switzerland. The motivation for grouping these together is that waste has to be processed here, heat cannot be transported over long distances and we assume that a similar level of domestic cement production as today is maintained. Therefore, excluding a Swiss CO_2 transport infrastructure means that CO_2 from these point sources cannot reach storage sites abroad. CO_2 may be used, however, for synthesis steps in P2X pathways.

The second type of CO_2 point sources are gas-turbine power plants as well as SMR and DAC plants. The first two deliver electricity and hydrogen, which can in principle be transported and therefore the plants can be placed outside of Switzerland. The latter deliver CO_2 and to minimise transportation costs are therefore ideally located close to storage sites abroad. For these reasons, gas-turbine power plants as well as SMR and DAC plants are still available in this scenario variant.

Figure 7 and Figure 8 show the results of this variant for the **Innovative** and **Conservative** scenarios. The main difference is the much higher contribution of DAC that has to compensate the lack of domestic CO_2 capture. This can also be seen in the high heat demand for CO_2 separation in Figure 9 that is satisfied by a larger share of solar thermal. As a consequence, the CO_2 avoidance costs (o) reach the aforementioned plateau already at lower CO_2 targets. Since the total costs are the integral of the marginal avoidance costs, this difference leads also to higher total system costs (r). Therefore, establishing a Swiss CO_2 capture and transport infrastructure has a clear financial benefit.

All other conclusions related to P2X pathways remain unchanged: besides a small contribution from electrolysis, no synthetic methane or kerosene/diesel is produced. The cost optimal solution is to import fossil gases and fuels and to compensate by DAC abroad.

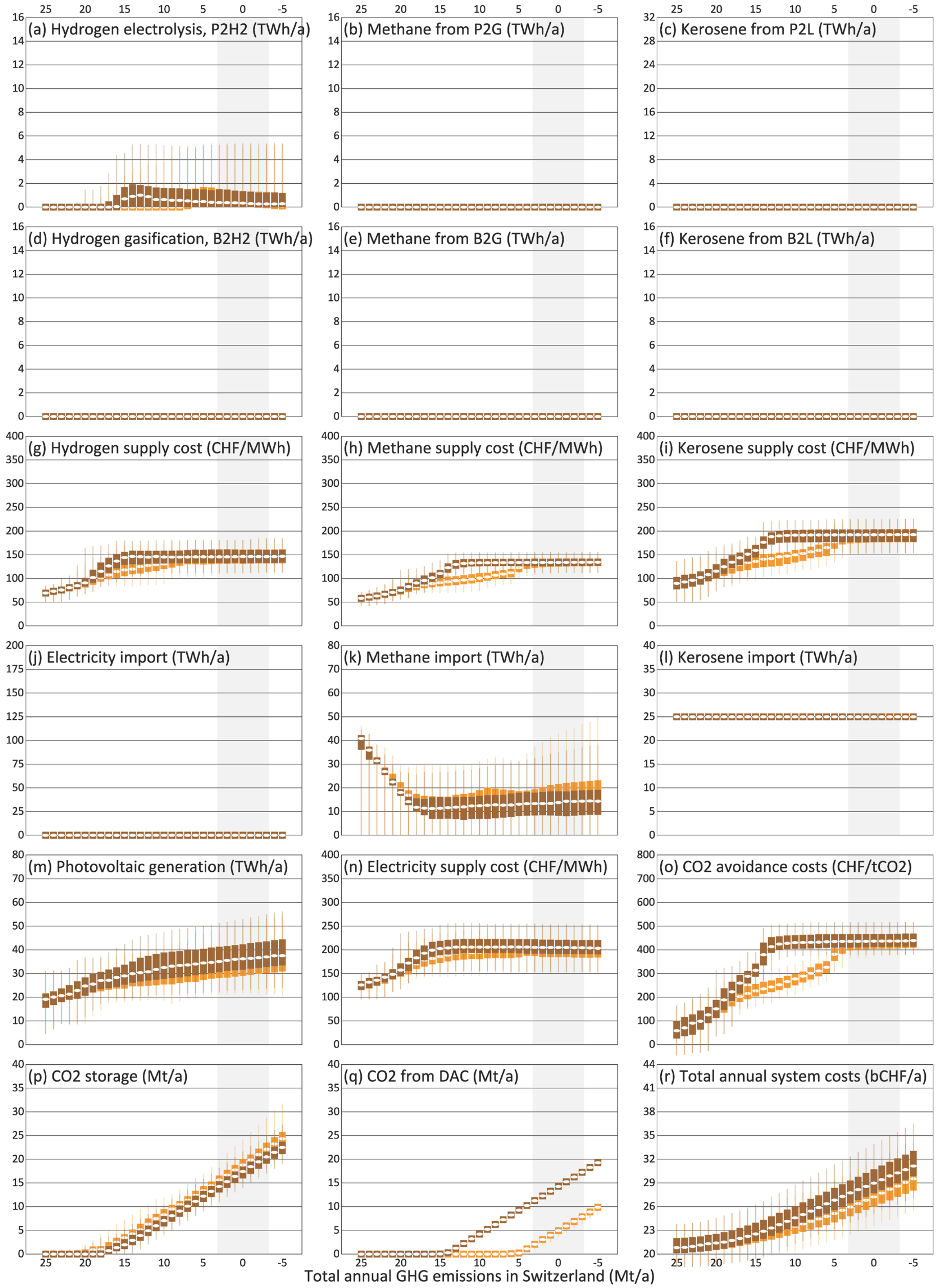

Figure 7: Variant of basic Innovative scenario: no CO_2 transport infrastructure in Switzerland; no electricity imports and B2X production pathways.

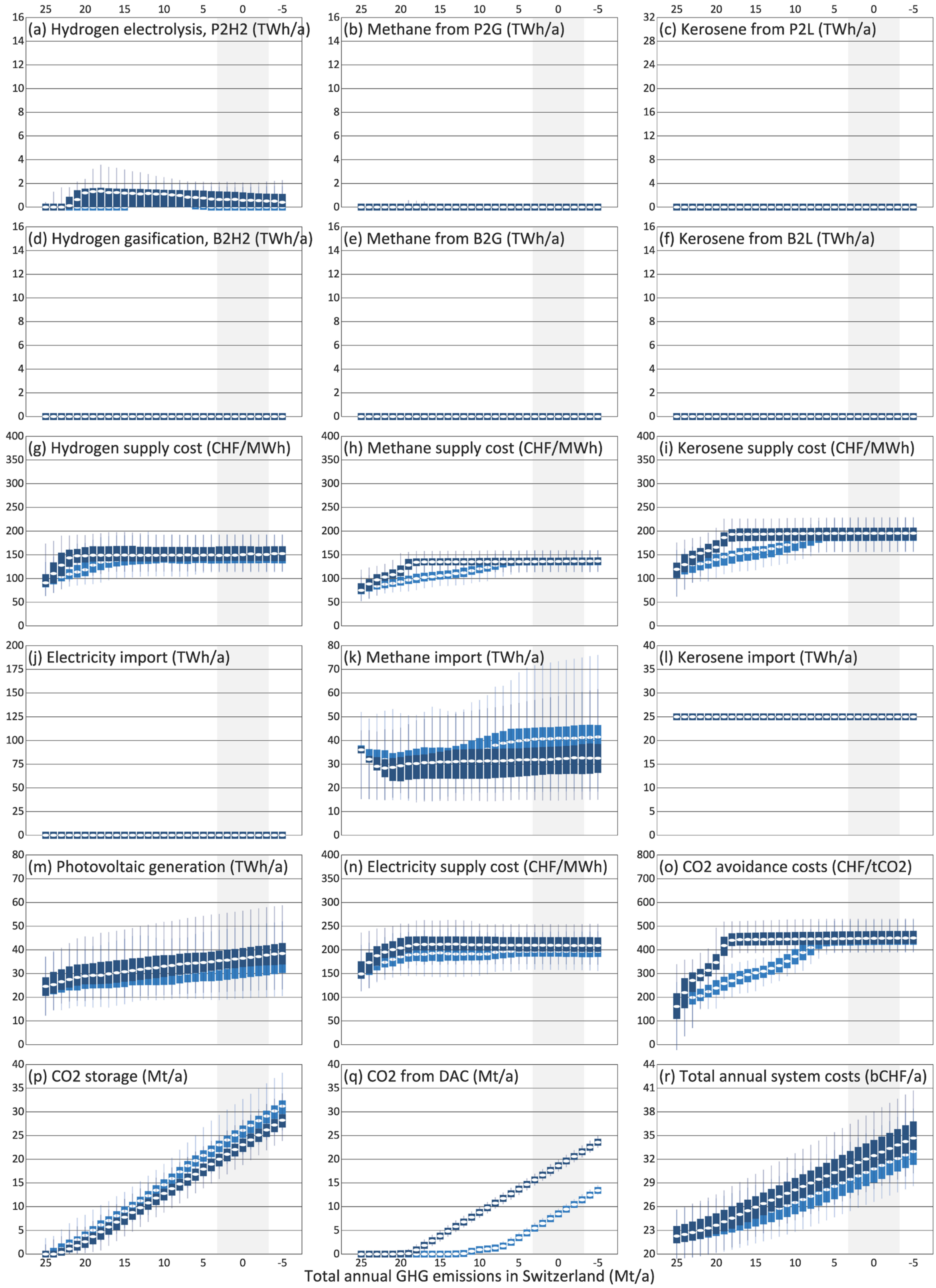

Figure 8: Variant of basic Conservative scenario: no CO_2 transport infrastructure in Switzerland; no electricity imports and B2X production pathways.

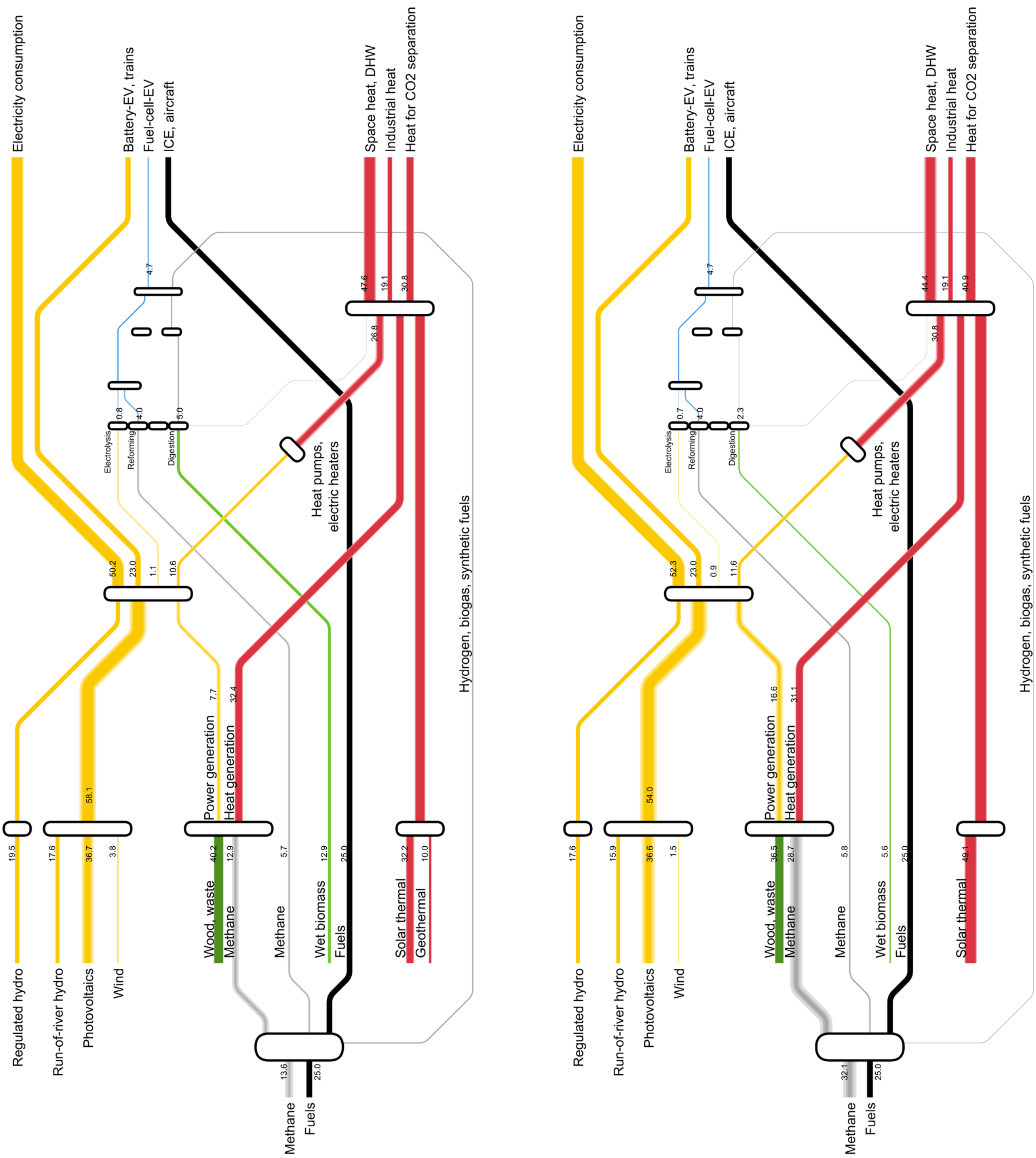

Figure 9: Energy flows in TWh/a for Innovative (left) and Conservative (right). Variant with no Swiss CO_2 transport infrastructure; 0 Mt/a: no electricity imports and B2X production pathways.

4.3 Scenario variants: limits on imports of methane and fuels

As listed in Table 3, we assume a methane and kerosene/Diesel import price of 30-60 CHF/MWh and 50-100 CHF/MWh, respectively. Figure 10 shows results for a variant of the **Innovative** scenario where **import prices are tripled**: imports of natural gas (k) drop to zero while kerosene imports (l) are not affected. The reason is that there are cost-effective alternatives to methane imports. Photovoltaic generation grows moderately (m), hydrogen electrolysis picks up (a), steam methane reforming is now done using domestic bio-methane from anaerobic digestion, etc. None of these options help aviation, therefore its energy demand is still satisfied with kerosene imports (l). Tripling the price of kerosene therefore just triples the price for aviation fuels, it does not (yet) lead to a change in production.

A similar picture can be seen in Figure 11. The **Conservative** scenario suffers from lower hydro power generation, less wood, absence of geothermal energy, etc. Therefore, a larger amount of methane imports is needed in any case (k). Even when **tripling the methane prices** there is still an import of up to 10 TWh/a. As a compensation there is also a higher growth in photovoltaics (m) and in electrolysis (a) compared to the respective **Innovative** scenario in Figure 10.

Starting again from the **Innovative** scenario we now consider a variant where **no imports** of natural gas or kerosene are allowed. As shown in Figure 10, kerosene is now produced by power-to-liquid processes (c). In order to achieve this, electrolysis increases massively and produces some 60 TWh/a of hydrogen (a). This requires large additional amounts of electricity as can be seen by photovoltaic generation that nearly quadruples (m). Note also that large amounts of CO_2 are now used (q) for the synthesis of kerosene, which come from large point source or direct air capture. This CO_2 is not stored anymore, therefore the underground storage declines (p). The same variant with no imports is considered starting from the **Conservative** scenario. As Figure 11 shows, the effect is the same with even higher amounts of photovoltaics, electrolysis and costs. As a consequence of these changes, the total energy system costs increase drastically (r).

Figure 10 and Figure 11 (g-i) show again the supply costs for hydrogen, methane and kerosene. Combining the information from the previous sections, the case of kerosene can be interpreted as follows: for the baseline import costs, Swiss kerosene needs are met by imports and emissions are compensated by negative emissions elsewhere in the energy system or abroad. Tripling the import price does not change this. The supply costs are still the import costs plus the CO_2 compensation costs. When no imports are allowed, the supply costs are the costs of producing this fuel in Switzerland, leading to strongly increased overall energy system costs. This means that in a scenario that does not allow for fossil imports of kerosene, any import of sustainable aviation fuels below a cost of 500-600 CHF/MWh would be cheaper than producing synthetic kerosene in Switzerland.

Figure 12 and Figure 13 show the energy flows for the two variants of tripled prices and no imports, respectively. Tripling of import prices leads to a sharp decrease of methane imports and hardly affects kerosene imports. The P2L pathway via electrolysis and FT-synthesis is already visible but at low levels. When imports are forbidden, photovoltaic generation increases strongly as does electrolysis and P2L. Note that the Diesel that is produced together with kerosene replaces hydrogen in non-electric passenger vehicles and is also used as replacement fuel in power & heat generation.

The same message is visible in Figure 14 that shows the annual generation and consumption pattern for hydrogen, kerosene and Diesel. The model is run with 24 typical days that represent a full year. The horizontal axis is time going from January to December. The days are resolved with 8 x 3h clusters. In the case of base import prices, hydrogen is produced by SMR and used for road mobility, kerosene is imported and used by aviation. When prices are tripled, SMR is not used anymore, hydrogen for road mobility is now produced by electrolysis that operates mainly in summer when photovoltaic generation is high. Winter demand is supplied via a seasonal hydrogen storage.

When imports are not available anymore, electrolysis increases strongly (note that the corresponding sub-figures have a 10 times larger scale). In the case of the **Conservative** scenario, no seasonal cavern storage is available. The fluctuating hydrogen production is buffered by a short-term storage to supply hydrogen to the P2L process at constant rate. Kerosene and Diesel are produced mainly during the summer months, and delivered in winter by a cheap fuel storage. The hydrogen buffer allows to operate the P2L process properly, however, due to the lack of a seasonal storage, the capacity factor of the P2L process is low, leading to higher investment costs. The changes when seasonal cavern storage is available for hydrogen in the **Innovative** scenario. Now hydrogen can be delivered to the P2L process throughout the year, leading to better economics for the P2L process. It can also be seen that Diesel is used as a fuel for road mobility and to generate power and heat in the winter months.

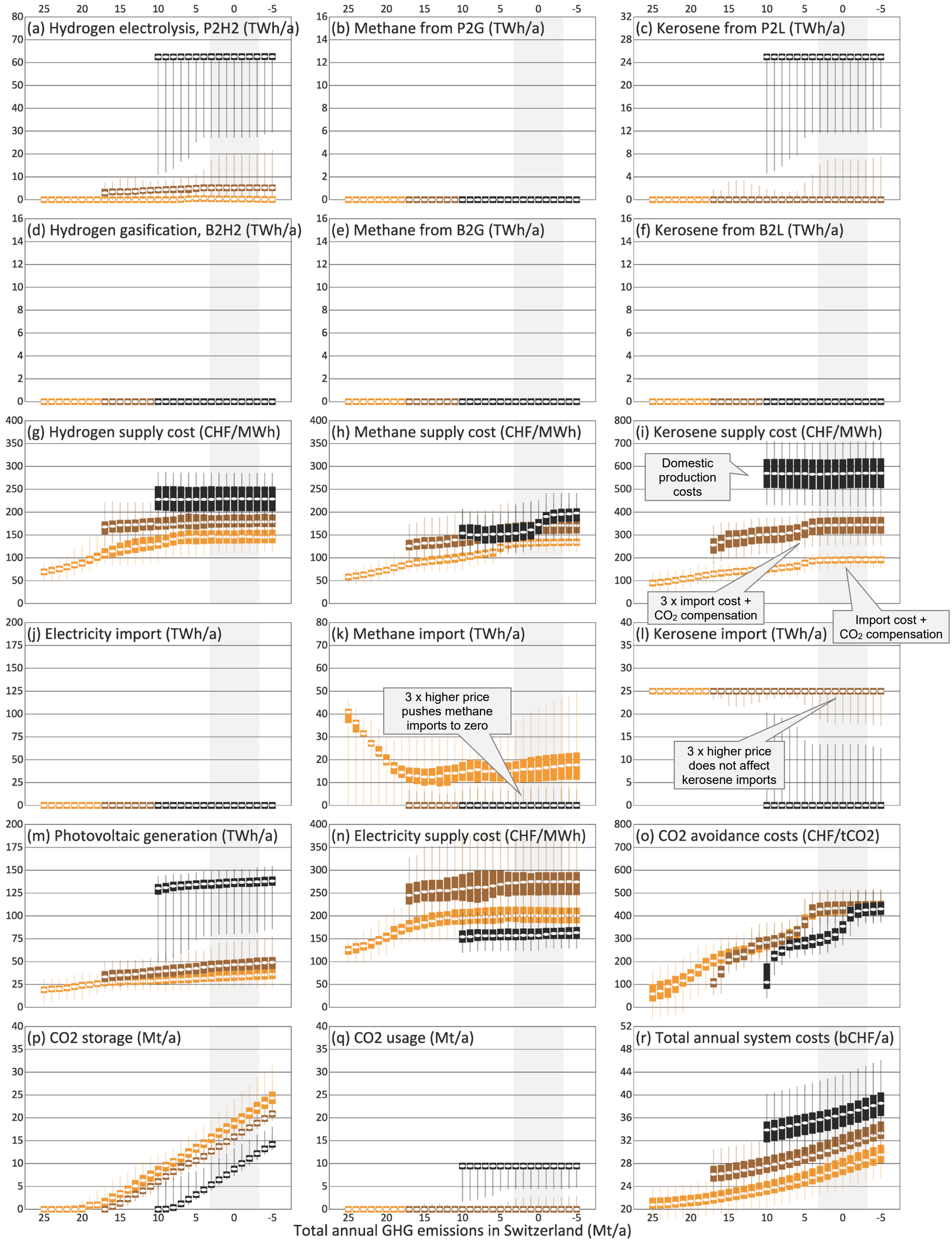

Figure 10: Variant of basic Innovative scenario: tripled import prices for methane and fuels; **no imports**; no electricity imports and B2X production pathways.

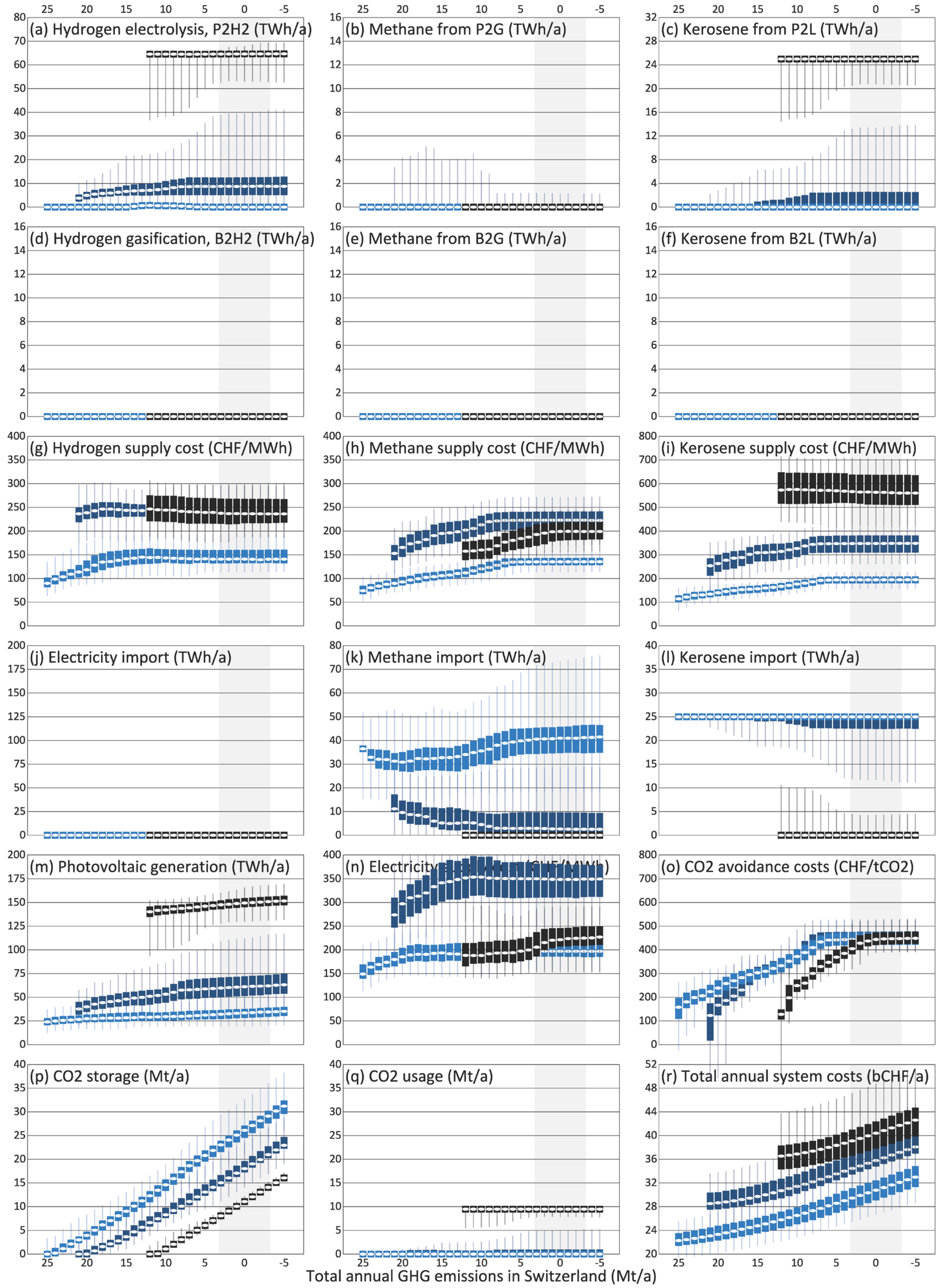

Figure 11: Variant of basic <u>**Conservative**</u> scenario: <u>**tripled import prices for methane and fuels**</u>; <u>**no imports**</u>; no electricity imports and B2X production pathways.

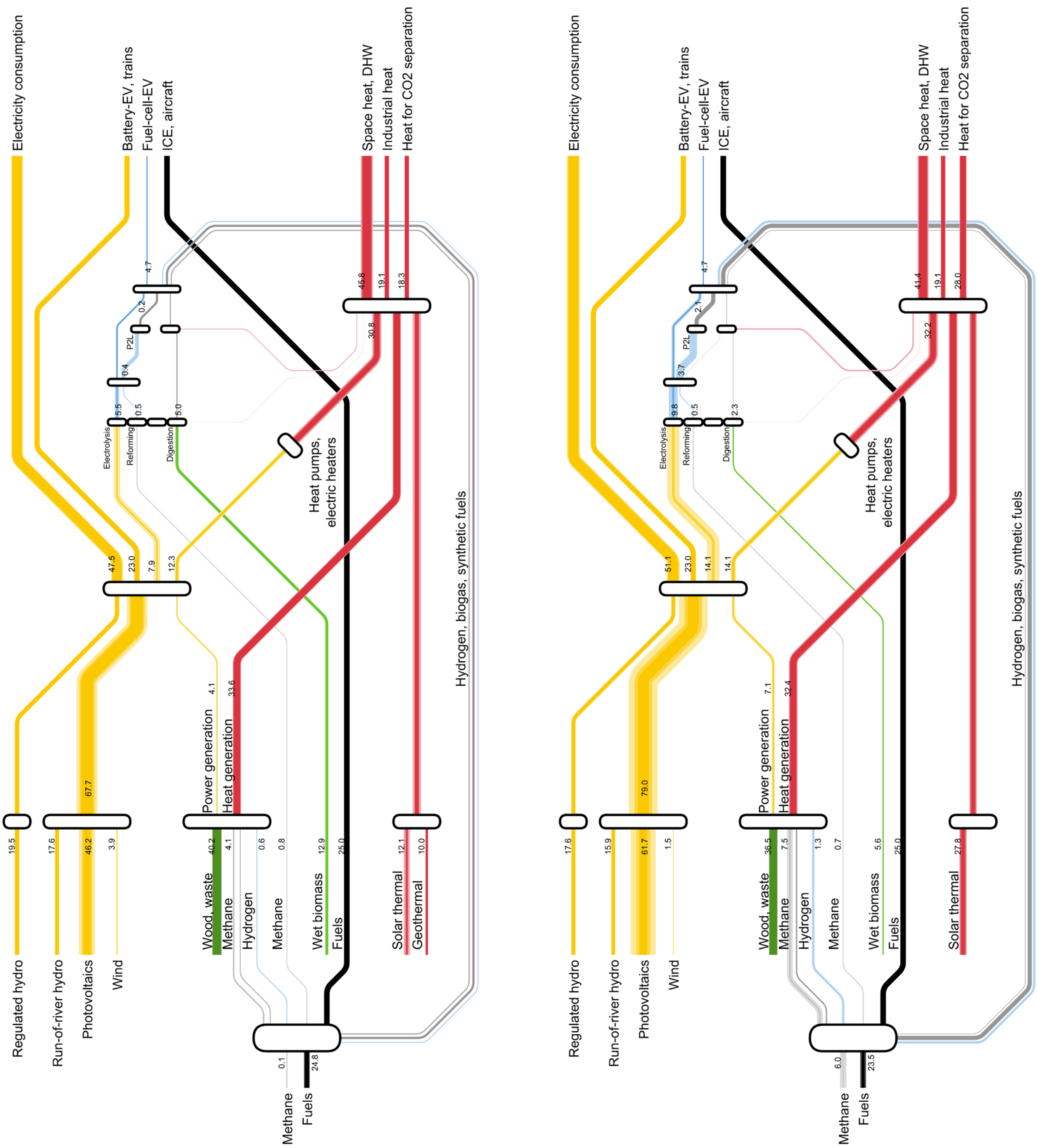

Figure 12: Energy flows in TWh/a for Innovative (left) and Conservative (right). Variant with tripled import prices for methane and fuels; 0 Mt/a; no electricity imports and B2X production pathways.

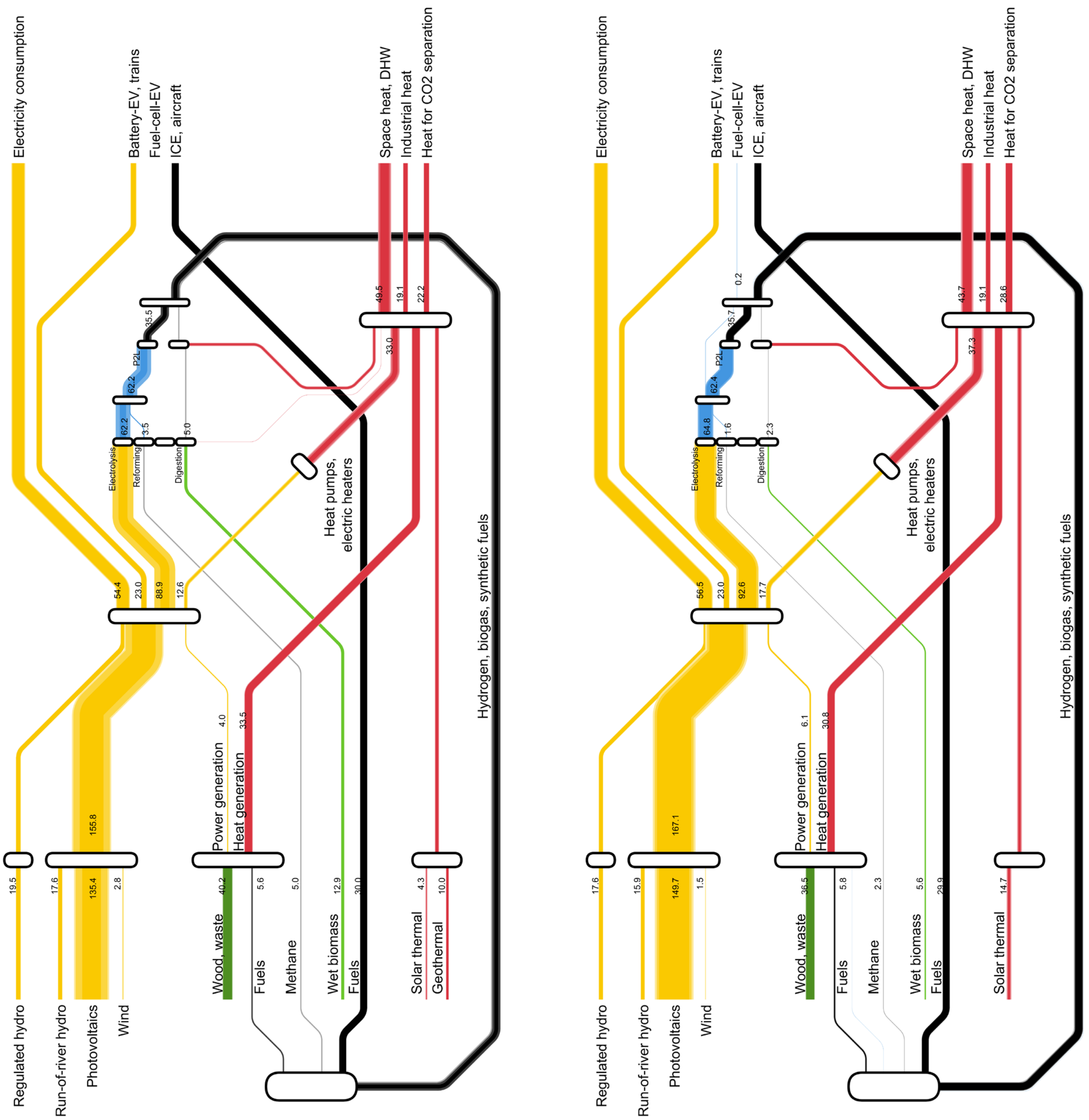

Figure 13: Energy flows in TWh/a for Innovative (left) and Conservative (right). Variant with no imports of methane and fuels; 0 Mt/a; no electricity imports and B2X production pathways.

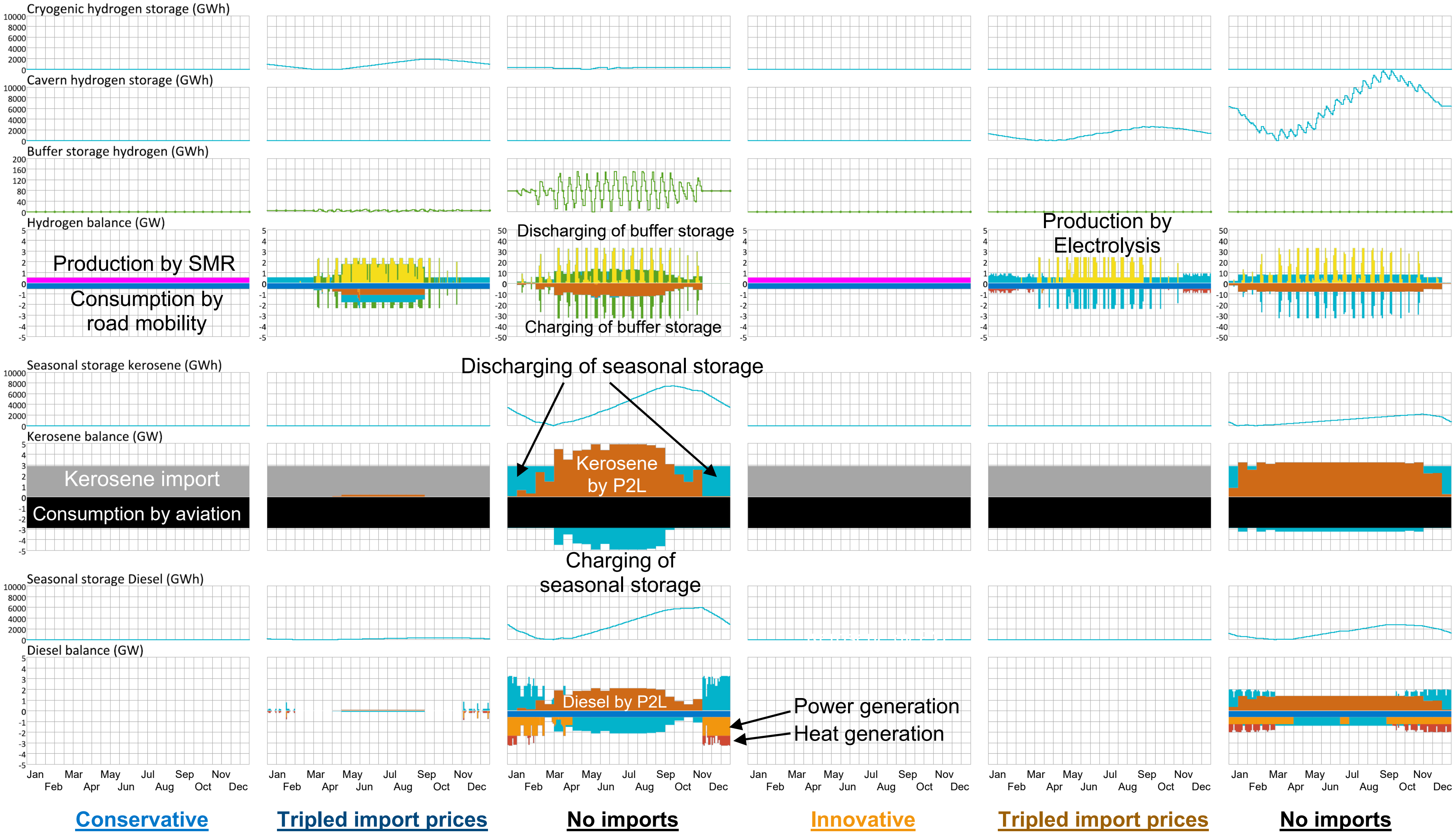

Figure 14: Generation and consumption of various chemical energy carriers; full resolution: 24 typical days, 8 x 3 h blocks; 0 Mt_{CO2}/a.

4.4 Scenario variants: electricity imports

The analyses in Sections 4.1 to 4.3 considered the full range of CO_2 targets to illustrate how key quantities vary along this axis. In the present section, we will focus on the net zero target, i.e., 0 Mt/a. We will vary again the import prices of methane and fuels, but now consider also electricity imports.

Figure 15 and Figure 16 show the results for the **Innovative** and **Conservative** scenarios, respectively. Each sub-figure contains four groups of results with six members. The six members start with the basic import price of 30-60 CHF/MWh for methane and 50-100 CHF/MWh for Diesel and kerosene, then continue with the price increased by factors of 1.5, 2, 3 and 5, and finish with no imports of methane and kerosene. Within the four groups, the left one is the case with no electricity imports, the other three have unlimited imports at prices of 150, 125 and 100 CHF/MWh_{el} (see labels in Figure 15 (h) and (n)).

The first observation has been made already. When the price for methane and fuels increases, first the import of methane declines quickly (k). This is more pronounced for **Innovative** than for **Conservative**. The main reasons are the lack of additional renewable resources such as geothermal, the reduced hydro power generation and the smaller hydro reservoirs. All these features are not available in **Conservative** and they increase the need for methane, for winter electricity production but also for industrial processes. The behaviour is very different for the import of kerosene. Only a five-fold increase of import prices leads to a reduction of imports (l) and to a domestic production of kerosene via a power-to-liquid process (c). This requires large quantities of hydrogen (a) that are produced by huge amounts of photovoltaics (m).

When considering electricity imports at varying prices, some of these insights are not sensitive to this change: the switch to domestic kerosene production still occurs only at much higher import prices, while the imports of methane quickly drop to zero. Also, hydrogen production for kerosene synthesis remains high. The main difference is photovoltaic generation (m) that decreases complementary to the increase of electricity imports (j).

We constructed the scenario variants along the axis of electricity imports and gas/fuel imports. The results include therefore also three types of extreme scenarios: (1) no fossil imports, (2) no electricity imports and (3) no imports at all.

The least problematic is the no electricity variant. As long as methane can be imported and there is the possibility to separate and store CO_2, electricity can always be produced domestically with gas turbine power plants, ideally of a size that can be integrated with district heating networks. The required methane quantities are between 20-40 TWh/a, which is similar to today. The lower end of this range can be achieved by realizing the innovations that differentiate the **Conservative** and the **Innovative** scenarios, i.e., to grow hydro power, geothermal energy, a better use of wet biomass to produce bio-methane, etc. A further reduction of the required methane quantities to 10 TWh/a seems possible by increasing photovoltaic generation.

Pushing fossil gas and fuel imports to zero has a detrimental effect on the energy system. Either photovoltaic generation grows to up to 150 TWh/a, five times higher than in the moderate variants discussed before, or electricity imports grow to up to 100 TWh/a, which is more than today's overall electricity consumption. The extra electricity from photovoltaics or imports goes into electrolysis, where the hydrogen is needed for the synthesis of kerosene via a power-to-liquid process. In summary, aiming at independence of kerosene imports requires unrealistic amounts of either electricity imports or photovoltaics. Reaching more than 100 GW installed capacity by 2050 (needed to produce >100 TWh/a) would require installations of 3-4 GW every year, more than the currently installed capacity. Extreme scenarios may be useful thought experiments but they cannot serve as a basis for robust policy recommendations.

Figure 17 shows the energy flows for the case of base import prices for methane and fuels, and electricity imports at 100 CHF/MWh_{el}. Comparing to Figure 6 shows that electricity imports reduce both the photovoltaic generation and the domestic power generation by gas turbines, reducing also methane imports.

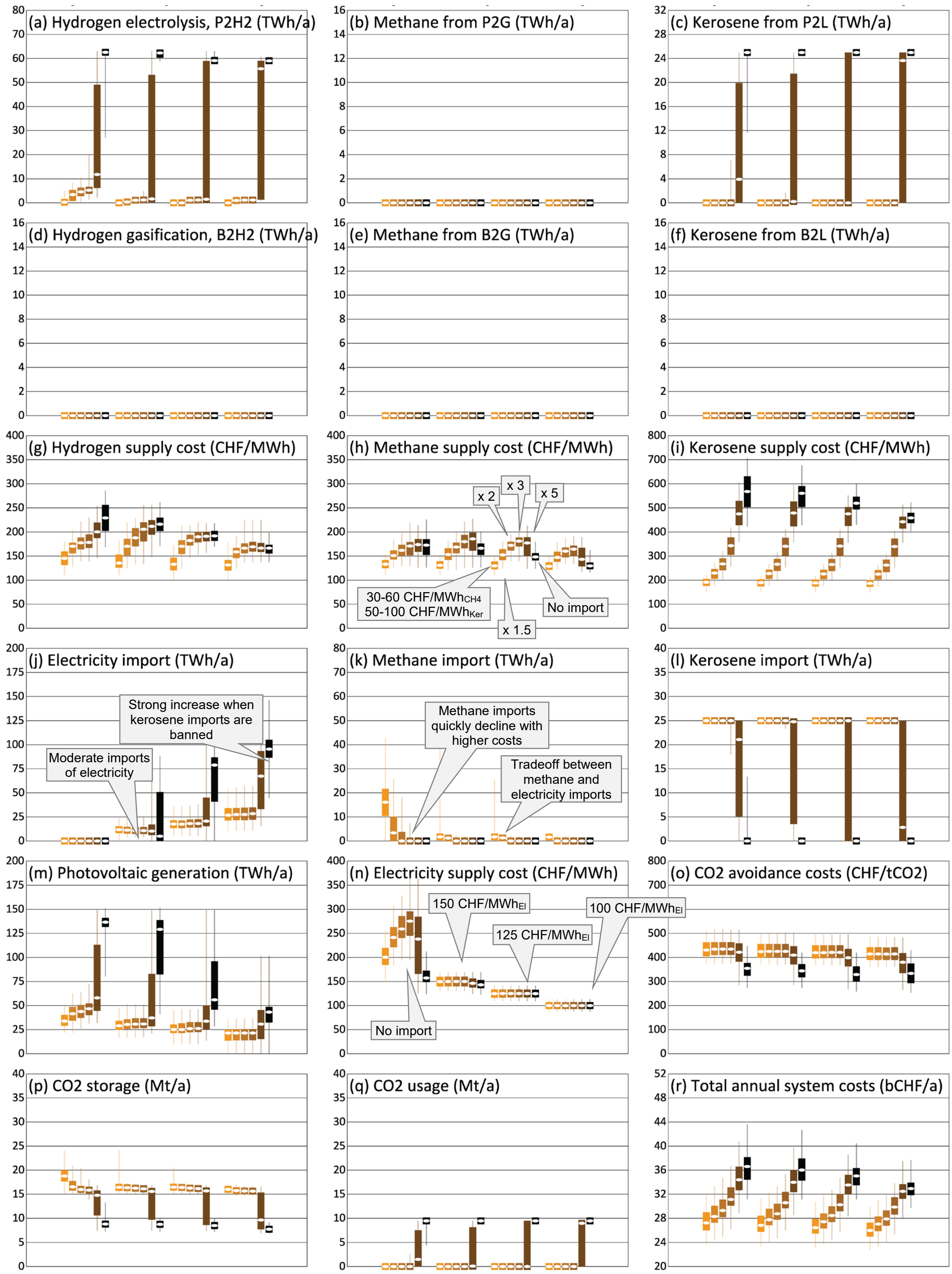

Figure 15: Variant of basic Innovative scenario: different costs for methane, fuel and electricity imports; 0 Mt/a; no B2X production pathways.

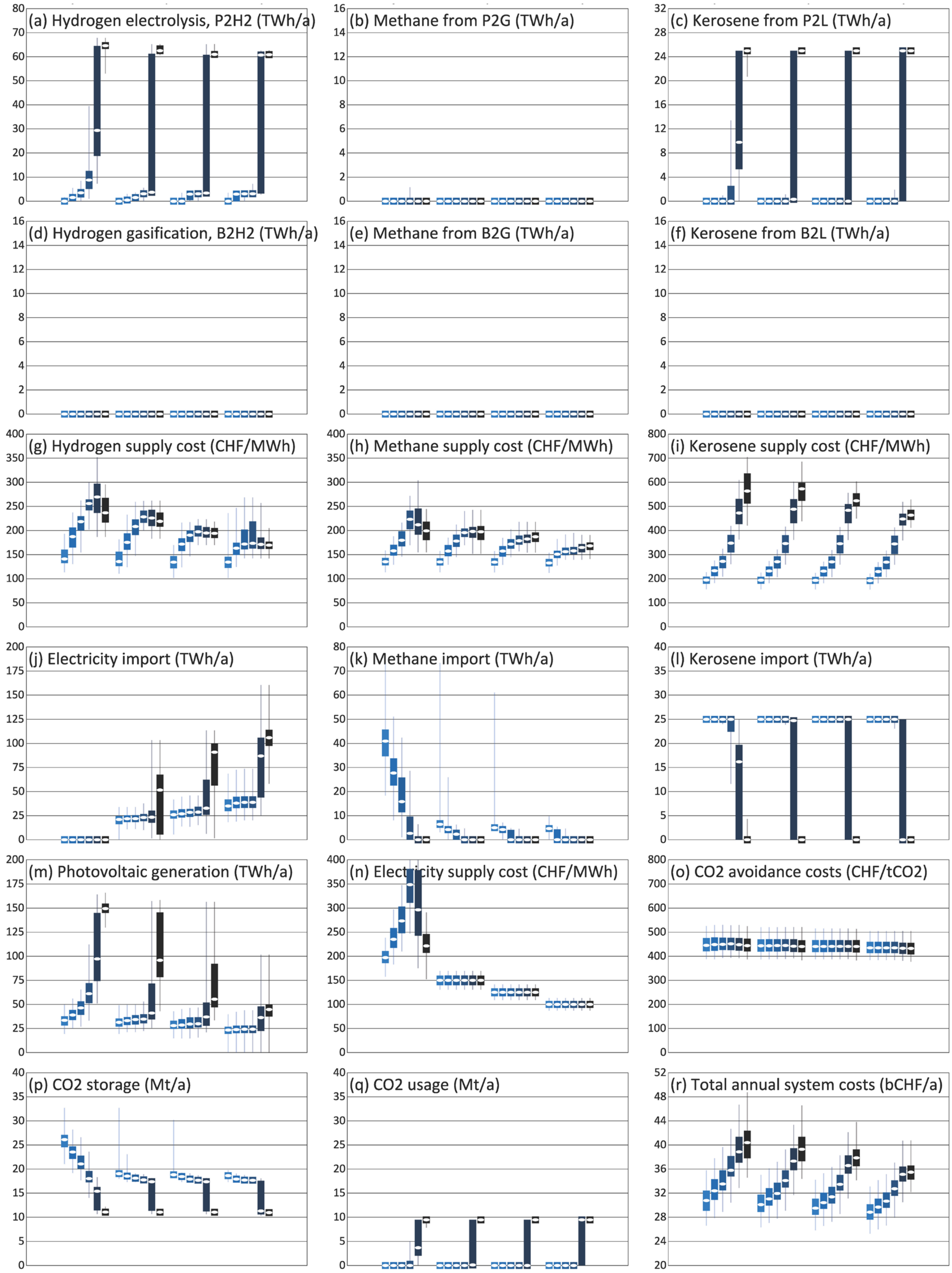

Figure 16: Variant of basic Conservative scenario: different costs for methane, fuel and electricity imports; 0 Mt/a; no B2X production pathway.

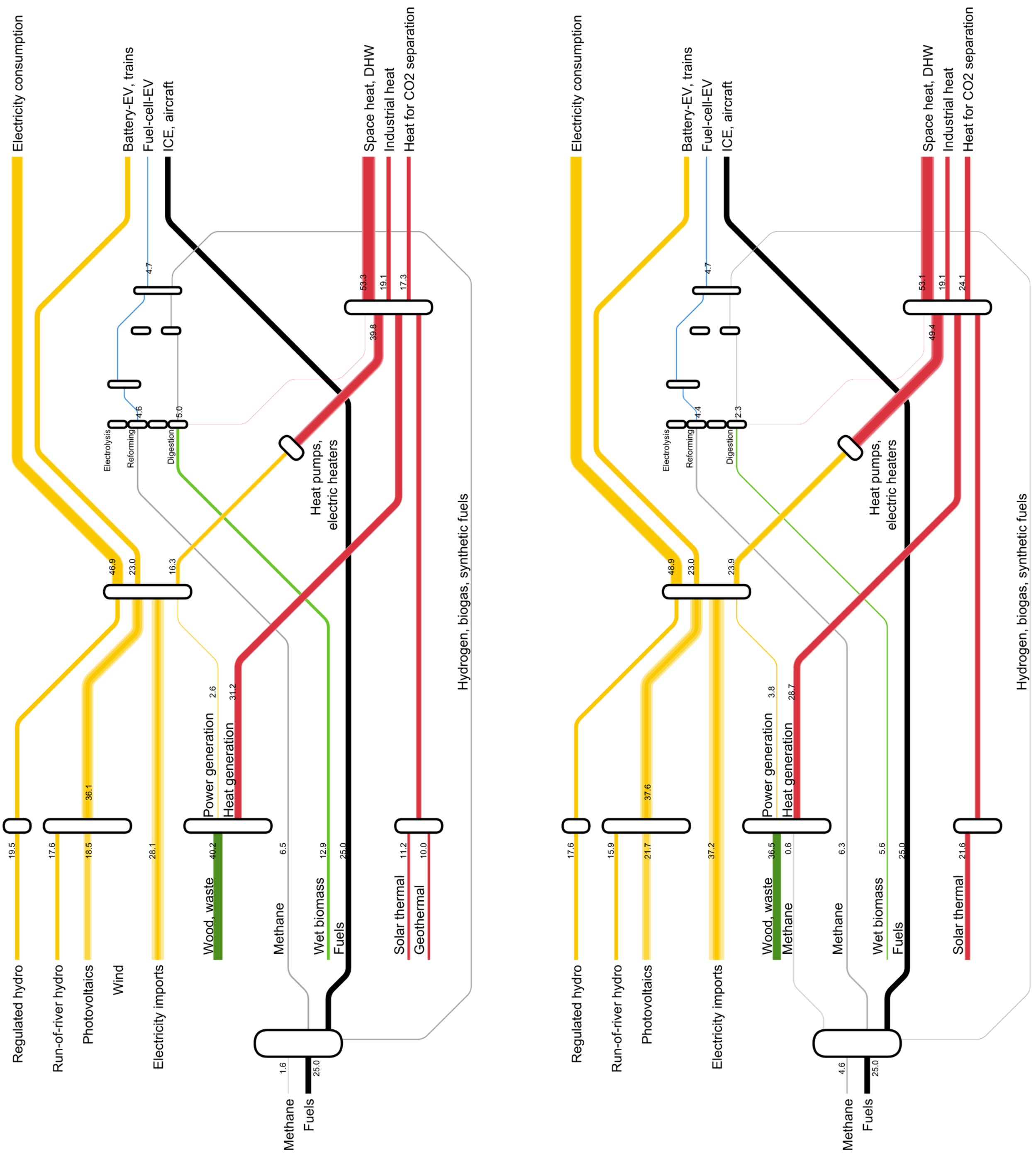

Figure 17: Energy flows in TWh/a for Innovative (left) and Conservative (right) scenario; variant with electricity import at 100 CHF/MWh; 0 Mt/a; no B2X production pathways.

4.5 Scenario variants: gasification-based B2X pathways available

As explained in Section 3.3, we excluded gasification-based B2X pathways from the basic scenarios. The reason was to better understand the potential role of P2X technologies. In this section we study the effect of releasing this constraint. The results are shown for the **Innovative** and **Conservative** scenarios in Figure 18 and Figure 19, respectively. Comparing with Figure 10 and Figure 11, it can be seen that only a few aspects change.

Hydrogen from biomass gasification appears for the basic import prices, replacing blue hydrogen from SMR with CCS. The reason is that biomass gasification can also generate negative emissions whereas blue hydrogen is at best CO_2-neutral when using fossil methane as feedstock. When import prices for methane and kerosene increase, biomass gasification shifts to B2L processes, whereas hydrogen is produced now with electrolysis. Note that the biomass-to-methane route is never chosen. The reason is that it has a lower potential than $B2H_2$ for generating negative emissions, since part of the carbon is in the product, and that methane is an energy carrier than can be replaced more easily than kerosene.

When imports are banned, a maximum of kerosene is produced via B2L, however, due to the limits on biomass availability this is only 5 TWh out of 25 TWh, the rest still being produced again by P2L. The picture is now very similar to the non-B2X case, simply with lower amounts of PV generation and electrolyzed hydrogen. In summary, gasification-based B2X processes are deployed when available, they are however limited in their potential by the availability of biomass resources.

Figure 20 shows the energy flows for the case of no gas/fuel imports. This can be compared with Figure 13 and it can be seen that the availability of B2X pathways reduces the need for P2X pathways and therefore the amount of electrolyzed hydrogen and photovoltaic generation.

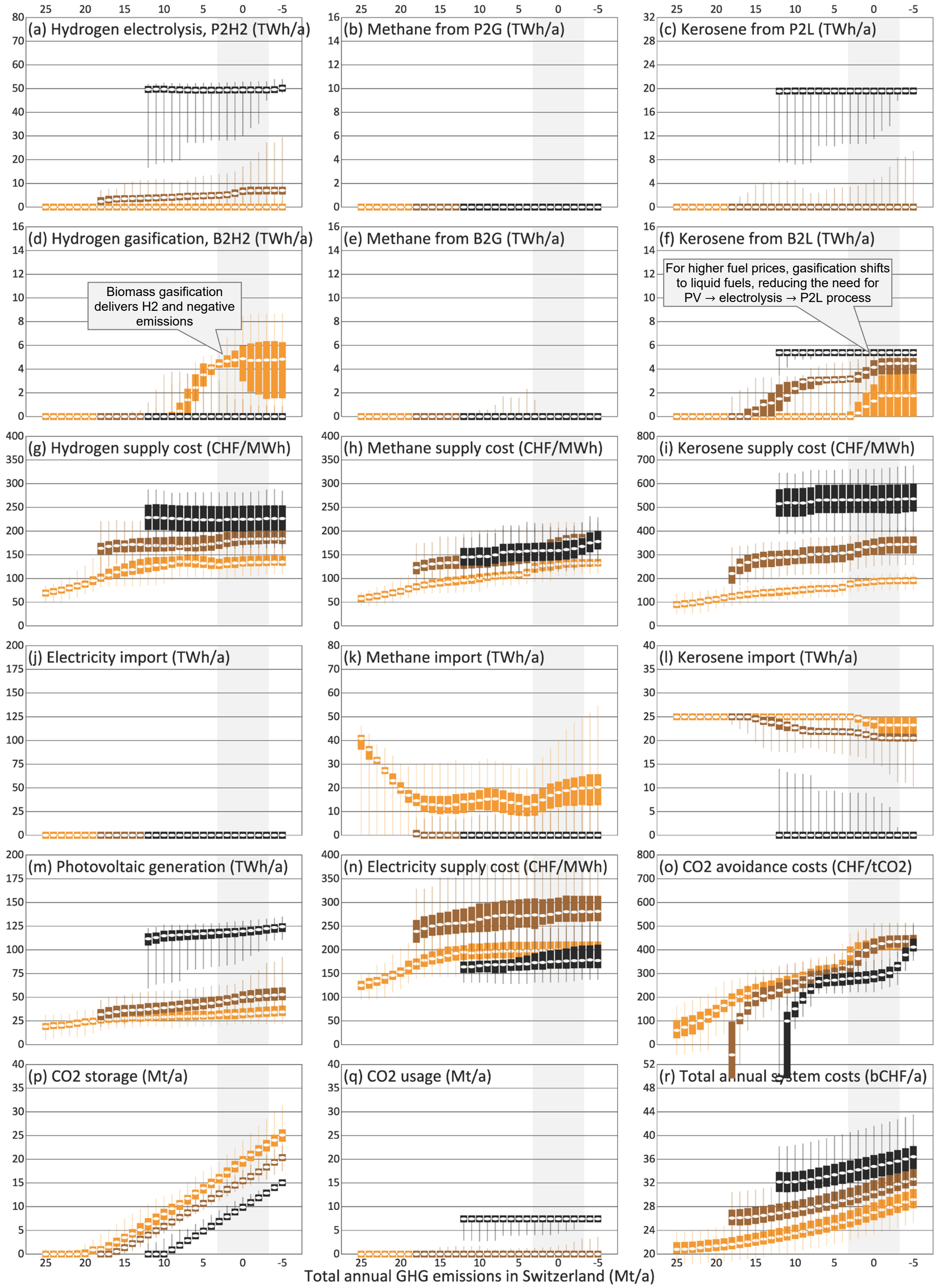

Figure 18: Variant of basic Innovative scenario: tripled import prices for methane and fuels; **no imports**; no electricity imports; B2X production pathways are available.

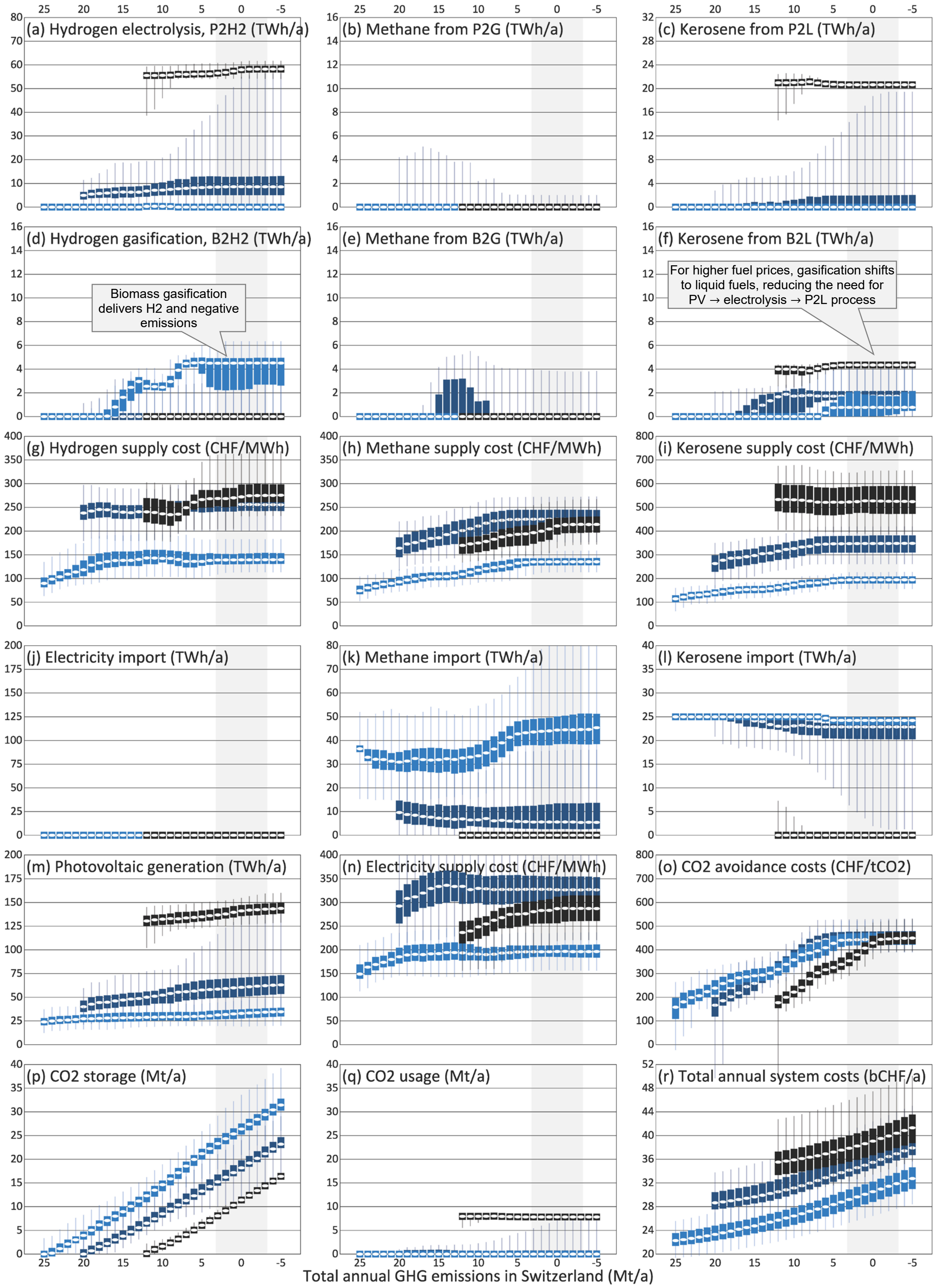

Figure 19: Variant of basic Conservative scenario: tripled import prices for methane and fuels; no imports; no electricity imports; B2X production pathways are available.

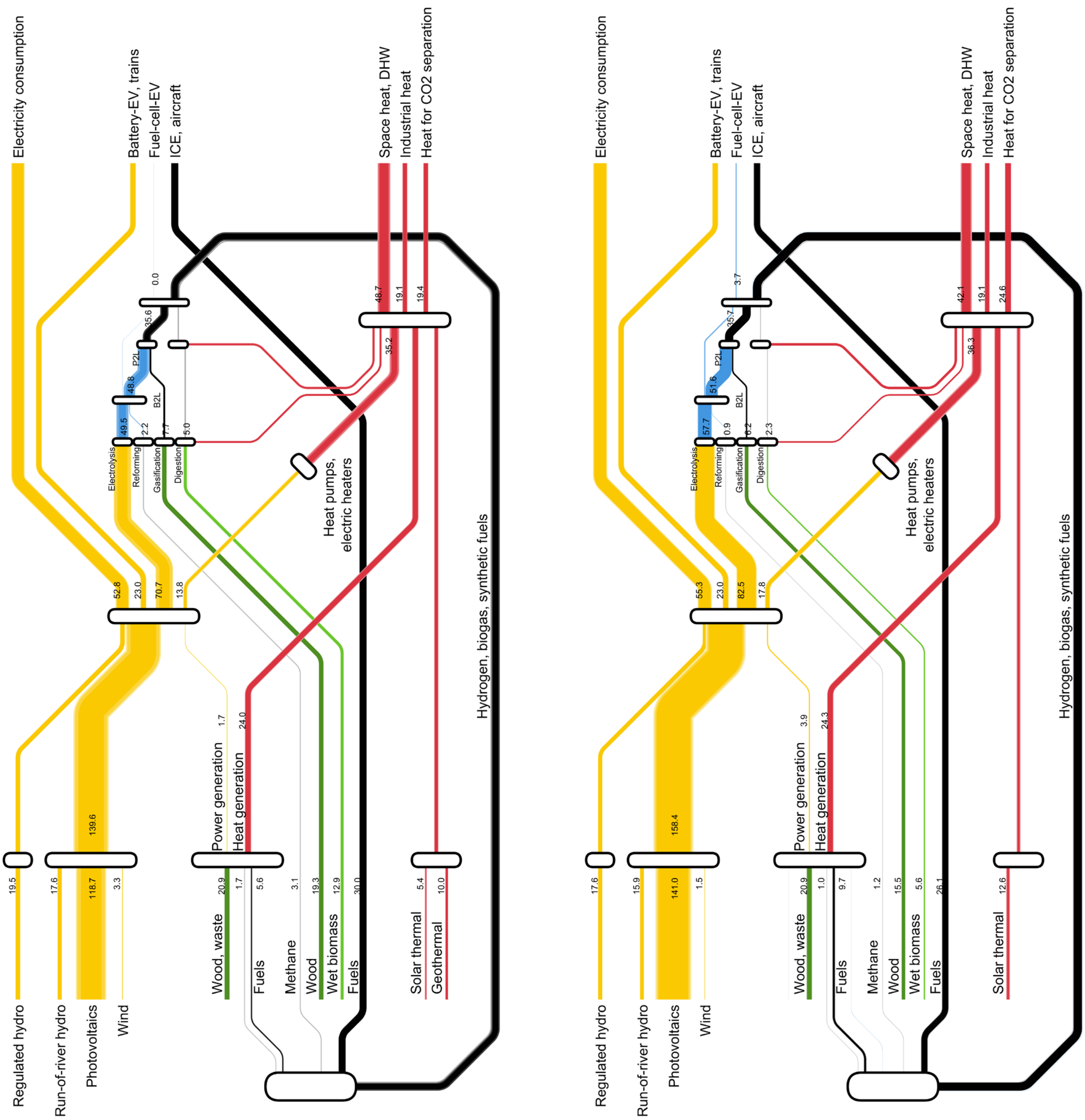

Figure 20: Energy flows in TWh/a for Innovative (left) and Conservative (right) scenario; variant with B2X pathways available; 0 Mt/a; no gas, fuel, electricity imports.

4.6 Scenario variants: Higher selectivity of FT-process for kerosene

As explained in Section 2, we assumed that Fischer-Tropsch processes will produce 70% kerosene and 30% Diesel as products. The question is whether this Diesel production is actually a benefit because it may be used for freight transport or as back-up fuel for power and heat generation. We study this effect by repeating the no gas & fuel import variants for the **Innovative** and **Conservative** scenarios. Figure 21 and Figure 22 show clearly that total costs and also the kerosene supply costs go down if a FT process could produce 100% of kerosene. From an overall system perspective, there is no benefit in producing a fraction of Diesel. Process developments that increase the kerosene yield of FT processes are therefore a valuable investment.

A caveat has to be added here: as explained in Section 3.3, we assumed that 50% of ton-kilometers in freight transport have to be provided by non-battery-electrical drive-trains, assuming that this sector cannot be fully electrified. The alternative options are hydrogen, Diesel & methane (fossil or synthetic). The model usually choses hydrogen as a complementary fuel, however, there may be sectors that require a liquid fuel. For instance, the Swiss army expects a consumption of 20 mio liter/a Diesel in 2050, corresponding to 0.2 TWh/a. This is less than 1% of the maximum P2L production that can be seen in the results so far.

4.7 Scenario variants: Higher selectivity and access to offshore wind

As explained in Section 3.1, there is no explicit model of the countries surrounding Switzerland and the resource potential of PV, wind, biomass, etc. is specific to Switzerland. All results so far indicate that a production of synthetic gases & fuels in Switzerland suffers either from a low availability of biomass (B2L pathways, see Section 4.5) or from the low capacity factors of photovoltaics and wind which will be 15-20% and 10-12%, respectively. The chemical processes in a P2L installation have to run at more or less constant rates. Matching the volatile nature of renewables with the demand for constant operation of a P2L plant can be done by different means that are all modelled in SES-ETH. First, the fluctuation of electricity production can be smoothed by short-term storage using pumped hydro or batteries. This allows to run the electrolyser already at a higher capacity factor. Then the hydrogen that is produced by the electrolyser can be stored in a short-term buffer or if available in a seasonal hydrogen storage. This allows the final P2L plant to run at almost constant rate. All these storage requirements add up to the high costs of synthetic kerosene production in Switzerland.

It is not in the scope of this study to investigate where synthetic fuels could be produced, however, a simple thought experiment can shed some light on the issue. For this we assume that Switzerland had access to off-shore wind electricity (4000 full load hours per year, capacity factor of 45%, CAPEX of 2000 CHF/kW). The effect can be seen for the **Innovative** and **Conservative** scenarios in Figure 21 and Figure 22, respectively (we also assume the 100% selectivity from Section 4.6). Apparently, supply costs for kerosene could be as low as 300 CHF/MWh, values that are similar to the compensation strategy for tripled import costs in Figure 10 and Figure 11. This highlights once more the fact that Switzerland must secure imports of SAF from regions that are better suited for P2L processes.

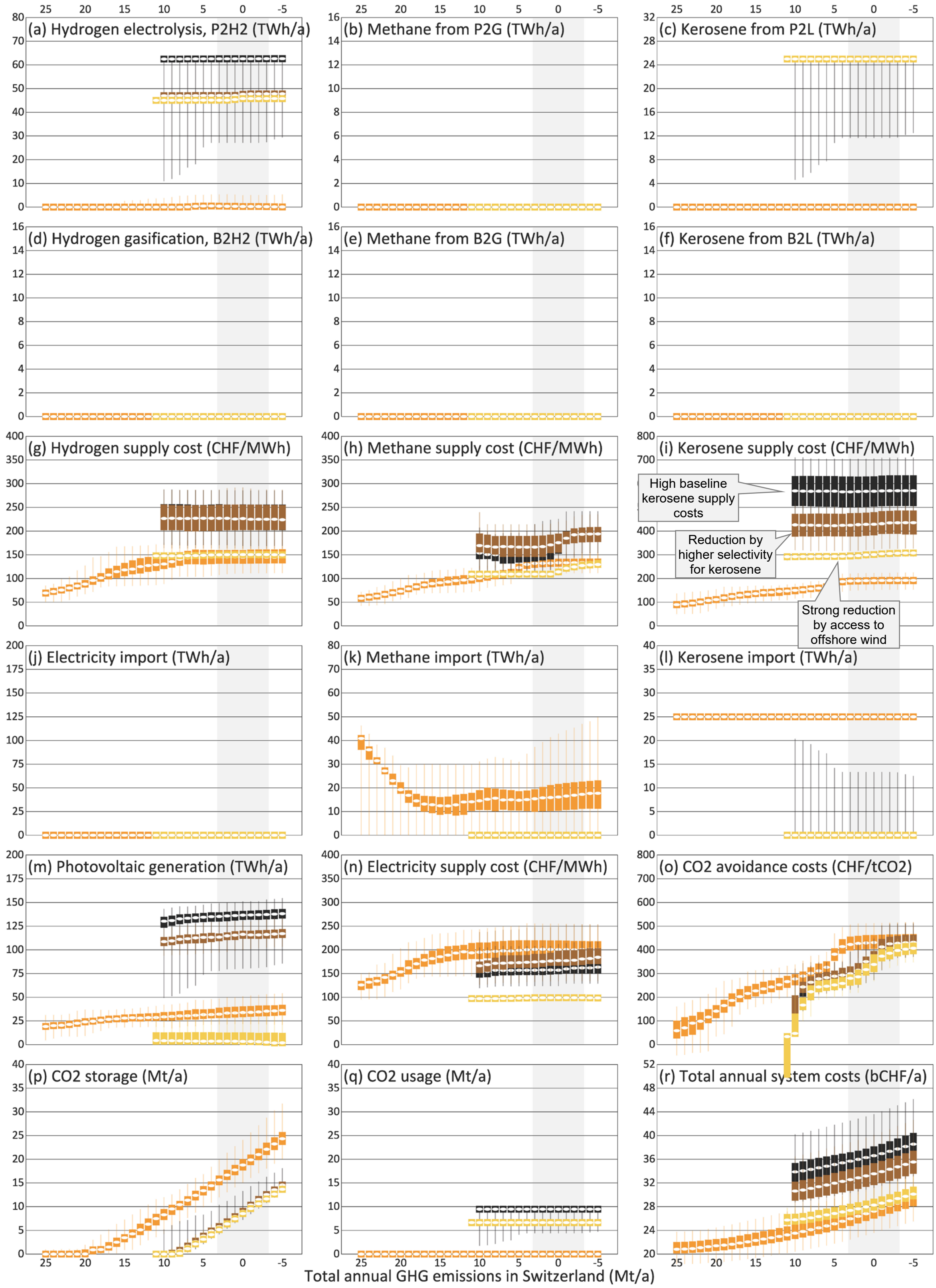

Figure 21: Variant of basic Innovative scenario: no gas & fuel imports; 100% selectivity for kerosene, 100% selectivity and access to offshore wind; no electricity imports and B2X pathways.

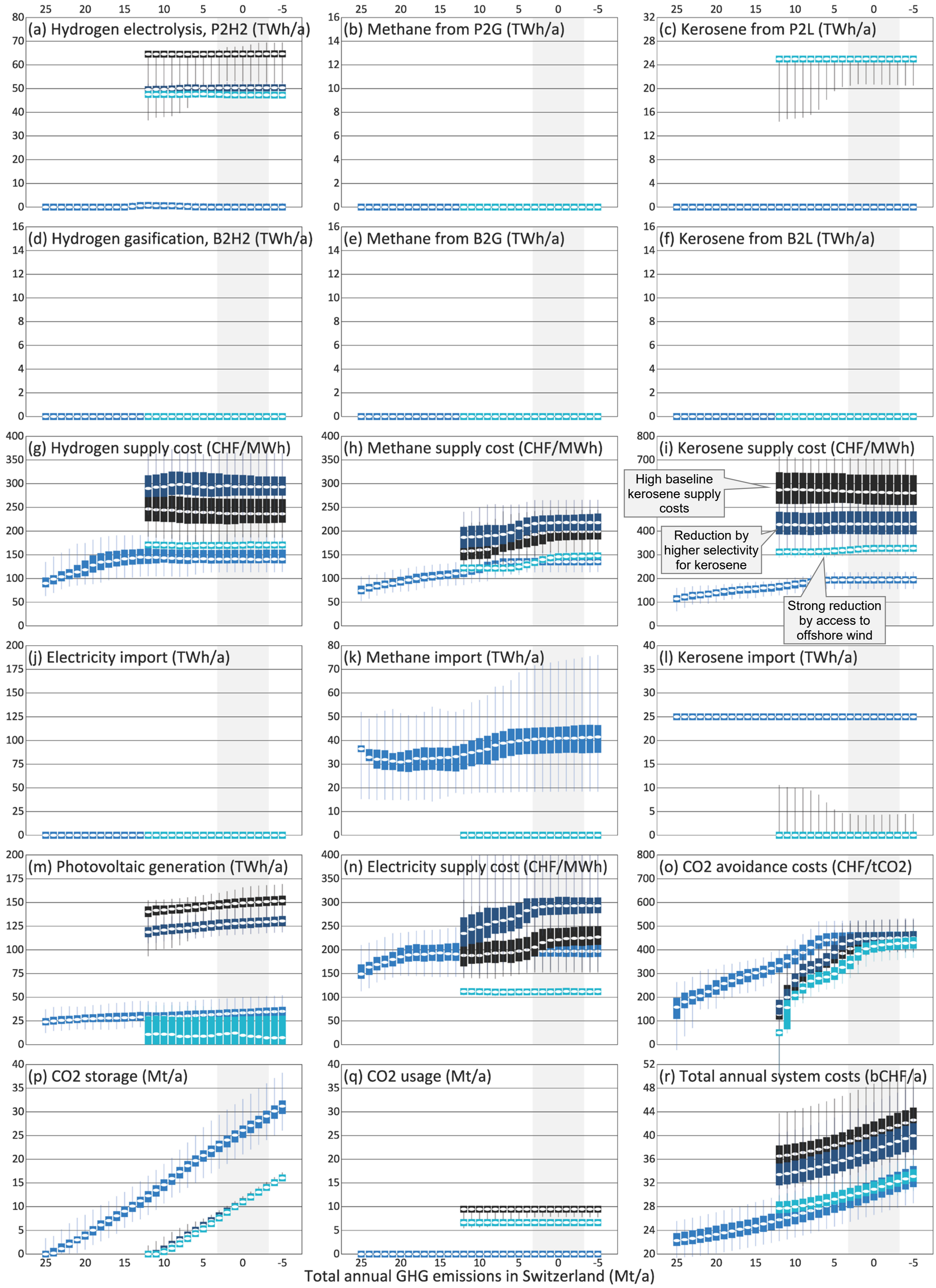

Figure 22: Variants of basic **Conservative** scenario; **no gas & fuel imports**; **100% selectivity for kerosene**, **100% selectivity and access to offshore wind**; no electricity imports and B2X pathways.

4.8 The role of synthetic gases & fuels as seasonal storage options

A major source of scepticism towards the energy transition is the lack of storage. What is often meant with this statement is that electricity from fluctuating photovoltaics as the major new renewable energy source cannot easily be stored seasonally, i.e., there is no means to transfer the "excess" of PV electricity from summer to winter. Hydrogen electrolysis combined with seasonal storage and re-electrification in winter via gas turbines or fuel cells is offered as a solution to the so-called winter-electricity-gap problem. While this is without doubt possible, the focus on photovoltaics and electricity alone can be misleading because the energy system is more than just the electricity system. The provision of heat and mobility services may suffer from the same issue of seasonal supply/demand mismatch but it offers also additional storage options that can help solving this challenge.

Figure 2 gave an overview of the various Power-to-X-to-Y pathways that are possible. We can now further analyse the result from the previous sections and answer the questions which of these pathways does actually show up in the context of the net-zero target. Note that we still follow the conservative assumption that no electricity imports are available. More specifically we look at the problem from two angles: (1) What is the role of thermal power plants in winter and (2) for what purpose is electrolyzed hydrogen used? Finally, we will also evaluate the energy storage volumes (in terms of TWh) for the different energy vectors.

We start with the provision of electricity in winter. The model foresees thermal power plants that are driven by methane, hydrogen or even Diesel as backup fuel. This type of plant generally operates only in the winter months, usually delivering also thermal energy to district heating networks. Figure 23 and Figure 24 show the output of these thermal power plants, split into the three aforementioned fuels.

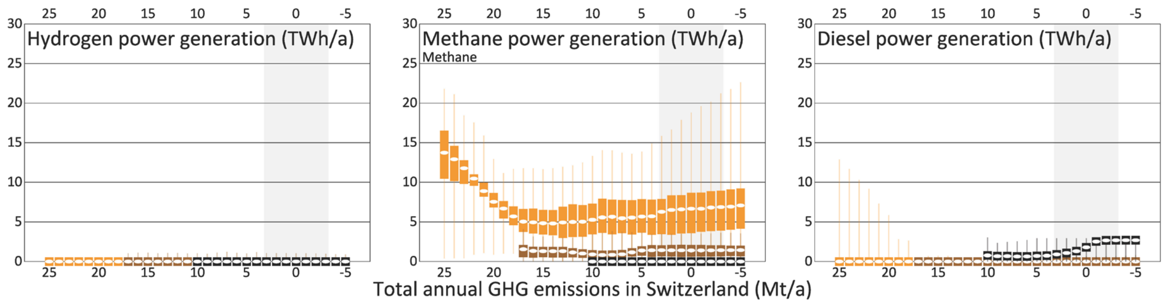

Figure 23: Winter electricity from thermal power plants; variants of basic Innovative scenario: tripled import prices for methane and fuels; no imports; no electricity imports and B2X production pathways.

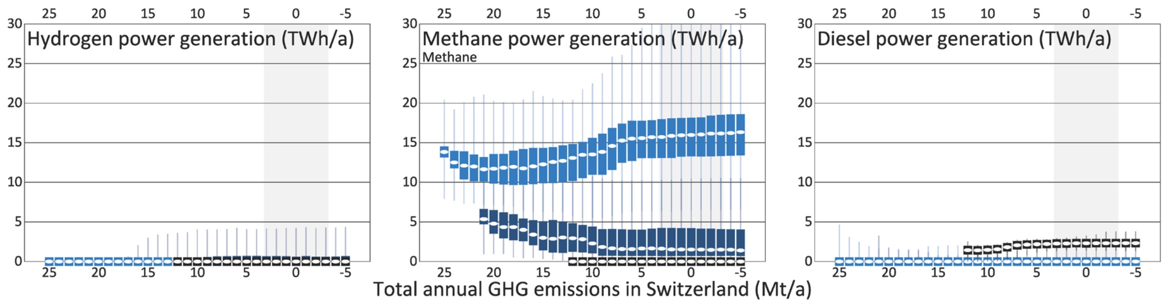

Figure 24: Winter electricity from thermal power plants: variants of basic Conservative scenario; tripled import prices for methane and fuels; no imports; no electricity imports and B2X production pathways.

In the case of basic methane and kerosene prices, thermal power plants are exclusively fuelled by methane. The resulting CO_2 emissions are tackled with CCS. The level of power generation is higher in the **Conservative** scenario. When gas and kerosene prices are tripled, power generation by methane is still the only chosen option, simply at a lower level. When imports of fossil gases and fuels are not available, thermal plants use Diesel as backup fuel that is produced together with kerosene for aviation. In any case, the thermal plant output in winter decreases when imported gases and fuels become more expensive or unavailable.

It is important to note that winter electricity demand is not a static target that simply needs to be satisfied by thermal power plants, e.g., via a power-to-hydrogen-to-power scheme. Figure 26 shows the electricity generation and consumption for a typical case (close to the median of the statistical distribution) at 0 Mt/a (8 x 3h blocks for each of the 24 typical days that make up a year). It represents the basic scenarios **Innovative** and **Conservative** with their variants of tripled import prices and no imports (see also the time series in Figure 14).

A number of observations can be highlighted. First, the base electricity demand is the same in all variants. It covers lighting, appliances, motors, etc. and we assume this portion to be inflexible, i.e., it has to be satisfied. Flexibility on the demand side comes from electromobility and the coupling to the heating sector. Here we assume that charging stations are available in a way that enough BEV are connected around noon to absorb part of the photovoltaic generation. Heat pumps and industrial electric heaters are operated also at peak photovoltaic generation, feeding into short-term thermal energy storage and seasonal thermal energy storage when available. Especially in the case of **Conservative** and **tripled import prices** the demand for heat pumps and industrial electric heaters is reduced. This has to be compensated by a re-allocation of other resources, such as wood or waste, by increasing the heat supply by solar thermal, or also by higher building renovation rates (not shown in the figure). A big consumer of electricity in the tripled import price and no import variants is electrolysis. The produced hydrogen is, however, not used for electricity generation, but it substitutes hydrogen from steam methane reforming for fuel-cell road mobility that has become uneconomic due to the higher methane prices (see also Figure 14).

Second, it can be seen on the electricity supply side that indeed the generation by thermal power plants reduces significantly for tripled import prices. As mentioned before, no hydrogen is used to drive this reduced generation. The methane that is still used is actually domestically produced bio-methane that has been shifted to the winter season with seasonal methane storage. Higher photovoltaic generation delivers the extra electricity in summer to run electrolysis, and also supplies more electricity in winter.

Third, when comparing the variants of **Conservative** to the variants of **Innovative,** it becomes clear that the extra electricity generation by thermal power plants is significantly reduced by all the measures that distinguish the two basic scenarios: higher hydro power generation and larger reservoir volumes help to produce more electricity in winter; seasonal thermal energy storage allows to run heat pumps in summer to save electricity in winter; centralizing wet biomass processing allows to increase the feed of bio-methane to the gas grid, etc. Finally, it has to be stressed that these scenarios assume no net electricity imports in winter. Any imports will further alleviate the so-called winter-electricity-gap problem.

None of the results so far show the relevance of storing electricity in the form of electrolyzed hydrogen (power-to-hydrogen-to-power) in a net-zero-scenario. This does, however, not mean that electrolysis plays no role. Figure 27 and Figure 28 show the hydrogen production and consumption for the basic scenarios and its variants. As could be seen already in Section 4.1, electrolysis is indeed absent from the optimum mix for the baseline import costs of methane and kerosene. Hydrogen for fuel-cell road vehicles is produced by SMR, if needed with CCS. However, a tripling of prices leads already to a shift from SMR to electrolysis. The consumption of hydrogen is still mainly for road mobility, with a small fraction used for power generation in the **Come together** scenario. Finally, when imports of methane and kerosene are banned, electrolysis increases strongly to supply hydrogen for the synthesis of kerosene and Diesel fuel. The latter is now used for road mobility, completely displacing hydrogen fuel-cell vehicles. Figure 25 summarizes the Power-to-X-to-Y pathways observed for the different scenario variants.

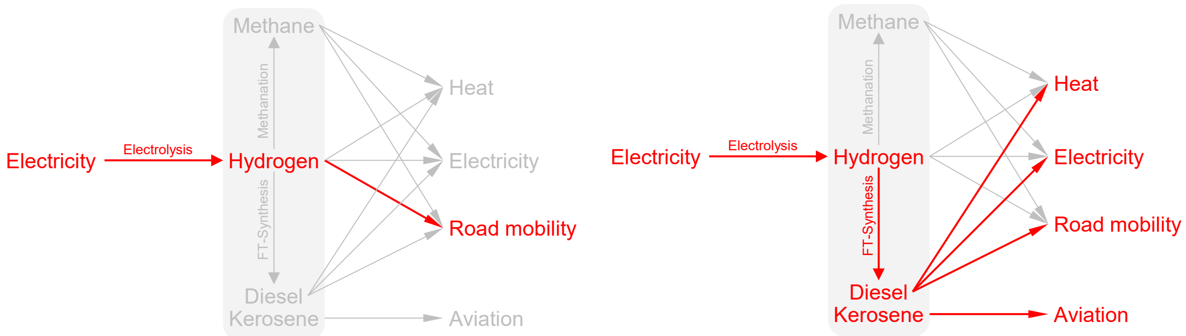

Figure 25: Power-to-X-to-Y options as observed for tripled import prices for methane and fuels (left) and for no imports (right).

In order to understand the role of synthetic fuels as seasonal storage options, it is also useful to display the resulting energy storage volumes in terms of TWh. Figure 29 shows these for the **Innovative** base scenario (see Figure 15 for the definition of the various data sets). Seasonal hydrogen storage plays no role for baseline fuel import prices. Hydrogen is produced via steam methane reforming with CCS and these plants can operate permanently to deliver hydrogen for road mobility (see also Figure 14). When import prices are increased, hydrogen is produced via electrolysis and this requires some seasonal storage to still deliver hydrogen to road mobility. When kerosene imports are banned, the need for seasonal hydrogen storage grows strongly, in line with the sharp increase of photovoltaics and electrolysis seen in Figure 15. This requires also a seasonal storage of the products, kerosene and Diesel. When electricity imports are considered, electrolysis is no longer driven by photovoltaics alone. Therefore, the need for storing hydrogen or kerosene decreases. Only Diesel is still stored seasonally, since it is used for winter electricity production in gas plants (see Figure 23). This may seem surprising since winter electricity can also be imported, however, Diesel arises as a by-product of kerosene, therefore its use makes economic sense.

The situation for the **Conservative** scenario in Figure 30 is similar with some differences that can be highlighted. The absence of a seasonal hydrogen storage in caverns forces the system to produce more kerosene in summer, increasing the need for seasonal kerosene storage. Only the short-term hydrogen buffer is used to avoid daily cycling of the FT-synthesis plant.

For both scenarios there is also some level of seasonal methane storage. This is however not related to synthetic methane from hydrogen and CO_2, there is simply a shift of bio-methane production from summer to winter. It can also be seen that large-scale thermal-energy storage used in connection with waste-to-energy plants or big heat pumps is deployed when available in the **Innovative** scenario. Last but not least, the increase of hydro reservoir volumes by increasing the dam heights is an option chosen in the **Innovative** scenario. The value of these measures decreases only when electricity imports become available in large quantities.

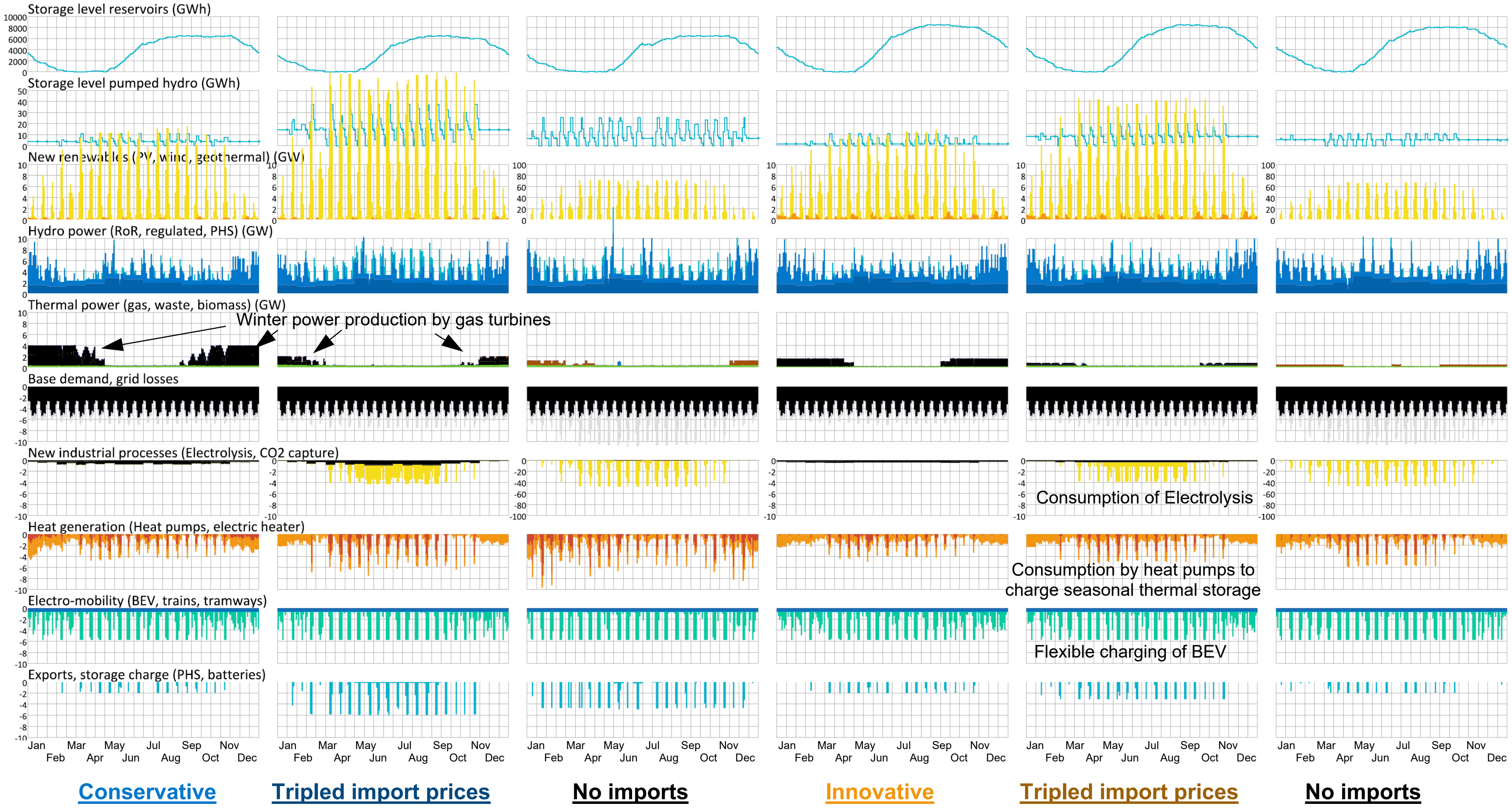

Figure 26: Electricity generation and consumption; full resolution: 24 typical days, 8 x 3 h blocks; 0 Mt_{CO2}/a.

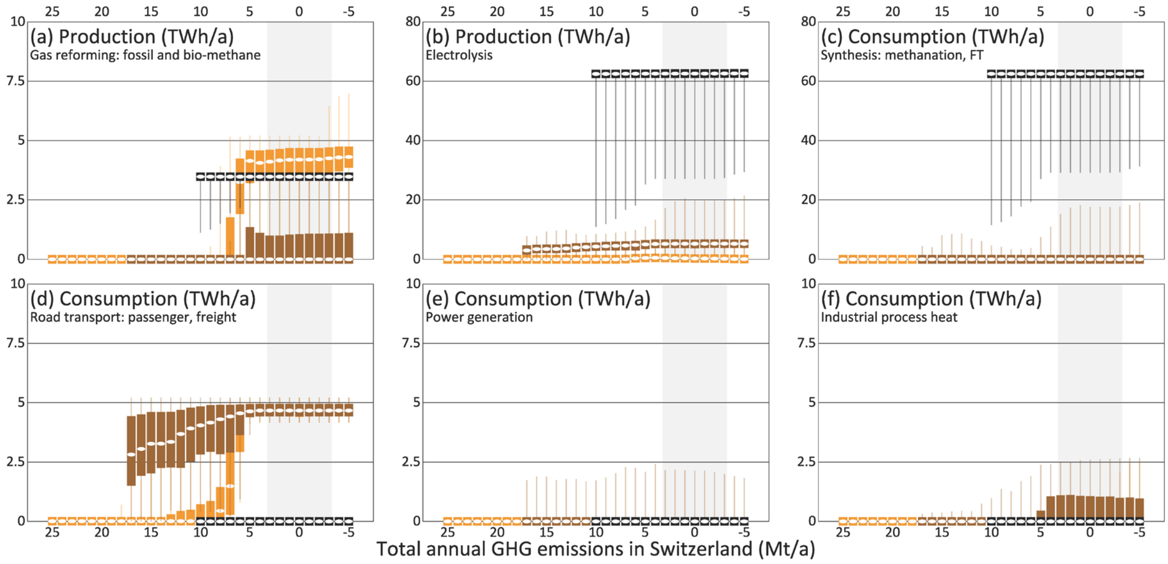

Figure 27: Hydrogen production and consumption; variants of basic **Innovative** scenario: **tripled import prices for methane and fuels**; **no imports**; no electricity imports and B2X production pathways.

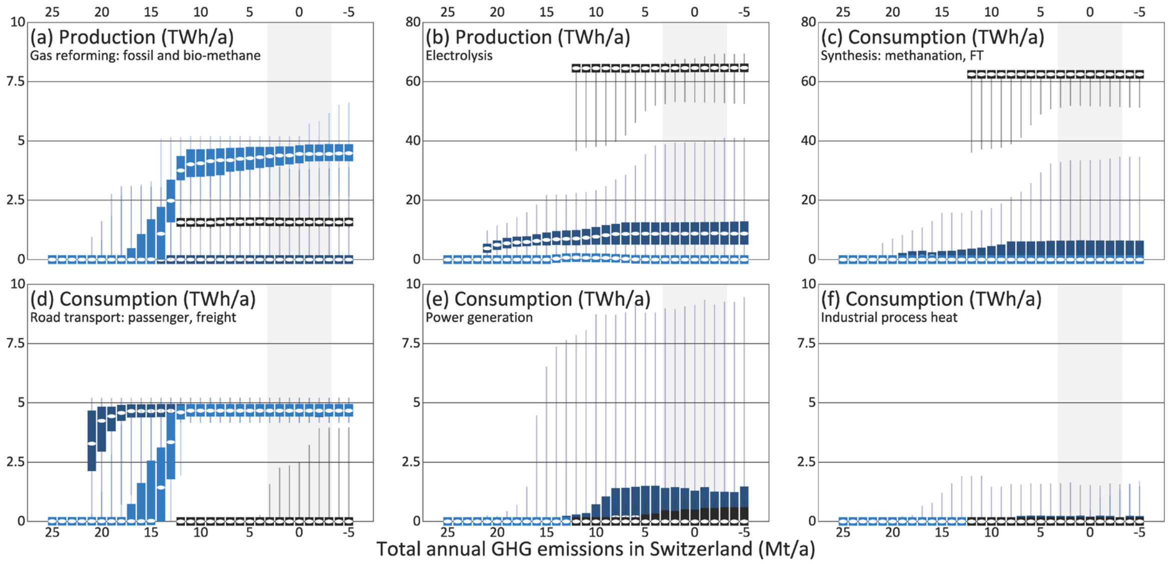

Figure 28: Hydrogen production and consumption: variants of basic **Conservative** scenario; **tripled import prices for methane and fuels**; **no imports**; no electricity imports and B2X production pathways.

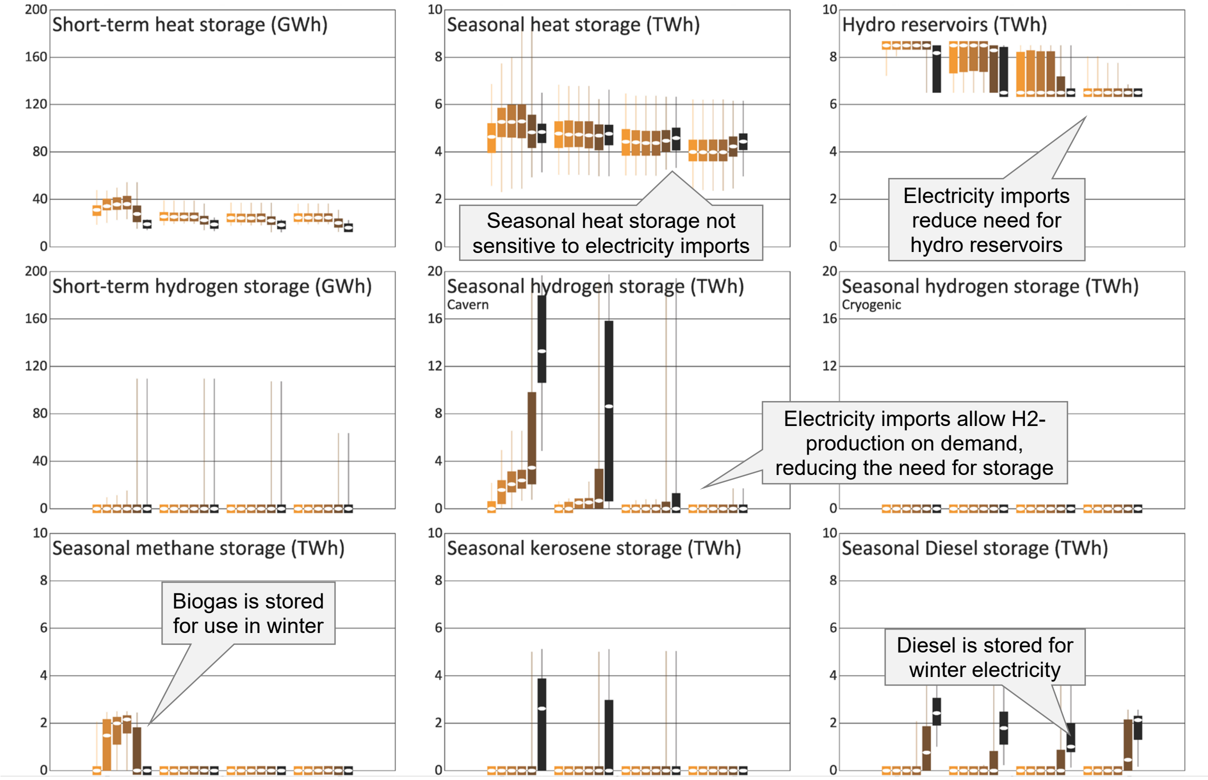

Figure 29: Effect on storage volumes: variants of basic Innovative scenario: different costs for methane, fuel and electricity imports; 0 Mt/a; no B2X production pathways.

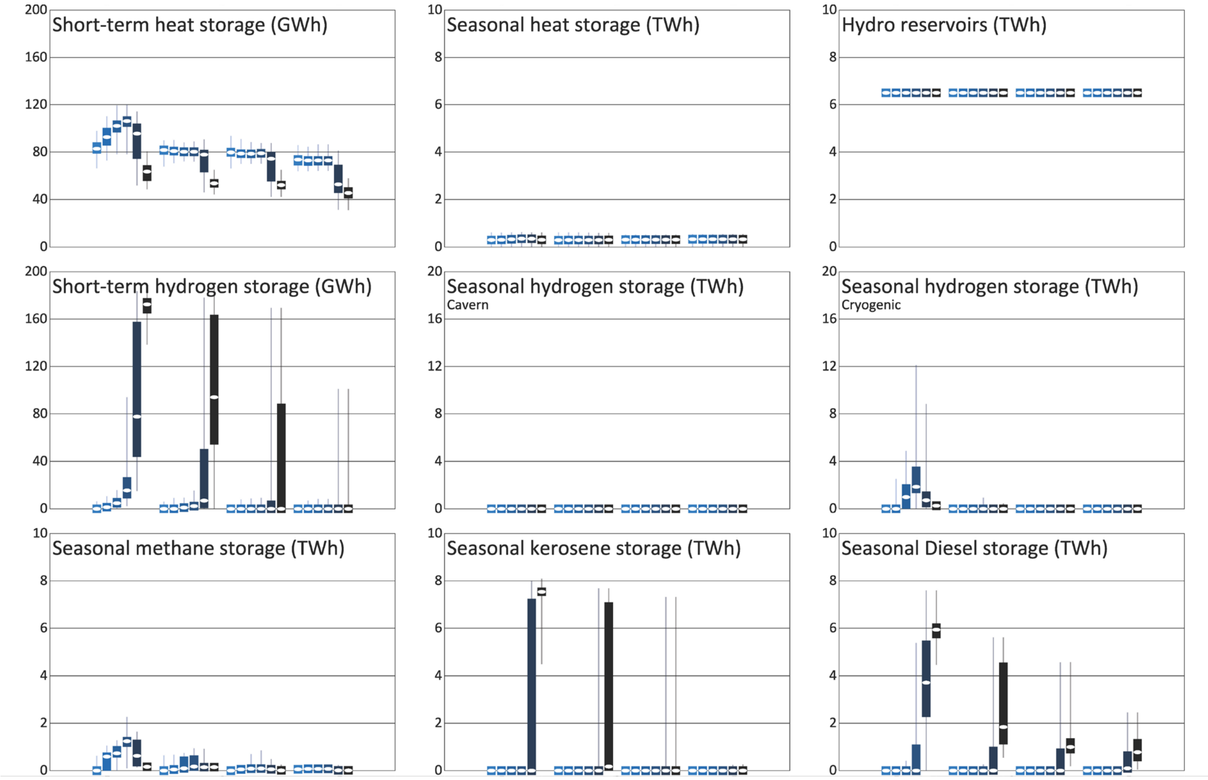

Figure 30: Effect on storage volumes: variants of basic Conservative scenario: different costs for methane, fuel and electricity imports; 0 Mt/a; no B2X production pathways.

4.9 Production cost curves for kerosene and hydrogen

As explained in Section 4.1, the model gives the marginal supply costs of a resource like kerosene or hydrogen. This is the cost of supplying one additional unit of the resource. However, this does not show the complete picture. We are usually interested not only in the cost of the last unit of a certain resource but in a curve of supply costs vs. quantity. In the electricity sector, such a curve is called a merit order curve.

We can generate this curve with SES-ETH with the following process: we choose 0 Mt/a as the net-zero CO_2 target. Then we assume that a certain quantity of the resource is available at a competitive price, i.e., at a price that is below the resulting marginal supply cost. For practical purposes we can also simply assume that this price is zero. We increase the availability of this quantity systematically, reducing thereby the domestic production volume. Figure 31 shows for kerosene that the marginal supply cost of the residual production decreases (note that the maximum production volume is 25 TWh/a as prescribed as an annual kerosene consumption). While the last unit of kerosene is produced at a cost of 500-600 CHF/MWh, the first unit costs between 300-400 CHF/MWh. A similar trend can be seen for hydrogen in Figure 32, where the maximum production volume was found to be 65 TWh/a.

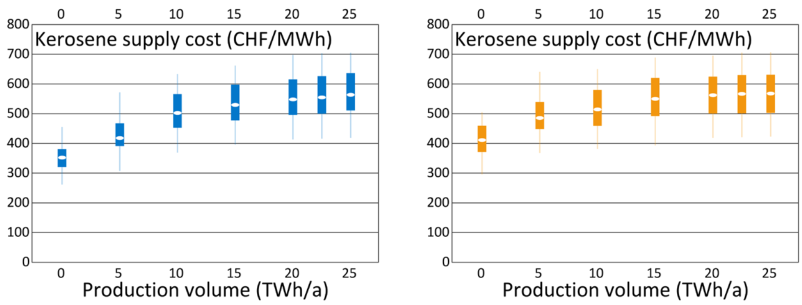

Figure 31: Production-cost curve of kerosene for **Conservative** and **Innovative** scenario; variant with no gas and fuel imports; no electricity imports and B2X pathways.

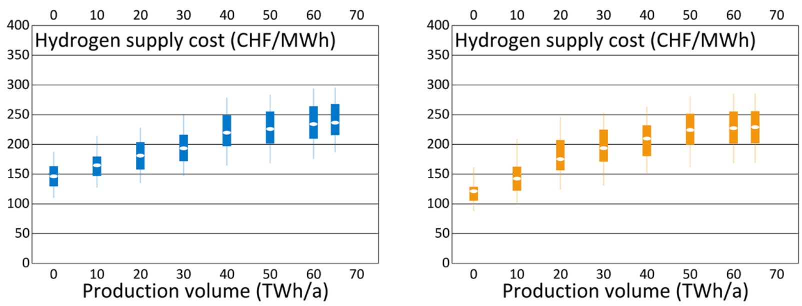

Figure 32: Production-cost curve of hydrogen for **Conservative** and **Innovative** scenario; variant with no gas and fuel imports; no electricity imports and B2X pathways.

5 Conclusions and discussion

We used an energy system model to analyze the future role of synthetic gases and fuels in the context of energy security and the Swiss net-zero emission goal. We defined two basic scenarios, a technology innovative and a conservative one. We added the additional condition that no electricity imports are allowed and excluded gasification-based Biomass-to-X (B2X) conversion pathways. The reason is to highlight the possible role of Power to-X (P2X) pathways, for instance as seasonal storage options. The following conclusions can be drawn from our work that are as insensitive as possible to the assumptions:

When methane and fuels like kerosene and Diesel are available at an import price of 30-60 CHF/MWh and 50-100 CHF/MWh, respectively, P2X pathways play no role in a net zero scenario. Hydrogen for road mobility is produced by steam methane reforming with CCS. Emissions from aviation are compensated by negative emission technologies. Additional electricity in winter is generated by methane-fired gas-turbine power plants with CCS. An essential element of this scenario is the separation of CO_2 from Swiss point sources, namely waste-to-energy plants, cement plants, and gas- or wood-fired combine-heat and power (CHP) plants. CCS avoids fossil emissions and allows to generate negative emissions that compensate emissions in aviation and agriculture. If the necessary CO_2 transport infrastructure in Switzerland is not available, emissions have to be compensated outside the country for instance by direct air capture (DAC). Since CO_2 capture from DAC is more expensive than from concentrated point sources, this results in higher total system costs.

Assuming a three-fold increase of import prices for methane and fuels leads to several changes in the optimal energy system for net zero. Methane imports drop considerably. Hydrogen for mobility is now produced with electrolysis. This requires higher amounts of renewable electricity production, which is mostly achieved by photovoltaics (PV). Electrolysers do not necessarily follow directly the PV generation, short-term electricity storage by pumped hydro or batteries creates a day/night balancing and allows electrolysis to run at higher capacity factors than PV. The balance of winter electricity is managed on both the supply and demand side: electricity supply from gas turbines decreases with the higher methane prices and increases with more PV. Electricity demand decreases with higher building renovation rates and a shift from heat pumps and electric heaters to wood and waste CHP plants. When seasonal thermal storage is available, large-scale heat pumps utilize the summer production of PV and save electricity in winter. The aforementioned effects are possible due to the coupling of the electricity and heating sector. Hydrogen from electrolysis is generally not used for power generation. Even with three times higher import prices for kerosene, emissions from aviation are still compensated by negative emission technologies and not by the production of synthetic fuels via Power-to-liquid (P2L) pathways.

P2L pathways appear only when the import of methane and fossil fuels is completely abandoned. This requires, however, a massive increase of PV generation and electrolysis. Synthetic kerosene is now used in aviation, while synthetic Diesel – a by-product of the P2L process – is used in road mobility and for power and heat generation. Overall system costs increase strongly.

The basic narrative changes little when electricity imports are considered. Methane imports go quickly to zero since winter electricity can be imported and gas turbines are not needed. When fossil fuel imports are banned, hydrogen electrolysis still increases dramatically to feed into kerosene synthesis by P2L, the only trade-off is to choose between unrealistic amounts of PV or unrealistic amounts of electricity imports. In both cases, the purpose of fuel independence is not well served: we will either depend on imports of electricity or on imports of an unrealistic number of PV panels.

The basic results do not change when gasification-based B2X pathways are considered. Biomass gasification with subsequent processing steps to deliver hydrogen and kerosene/Diesel is always part of the optimal mix. The reason is that B2X does not depend on renewable electricity generation (mostly photovoltaics) which suffers from low capacity factors. B2X installations use biomass and can run throughout the year, making better use of expensive installations. The downside is the limited availability of biomass, which is by far not sufficient to deliver all the required kerosene for aviation in Switzerland.

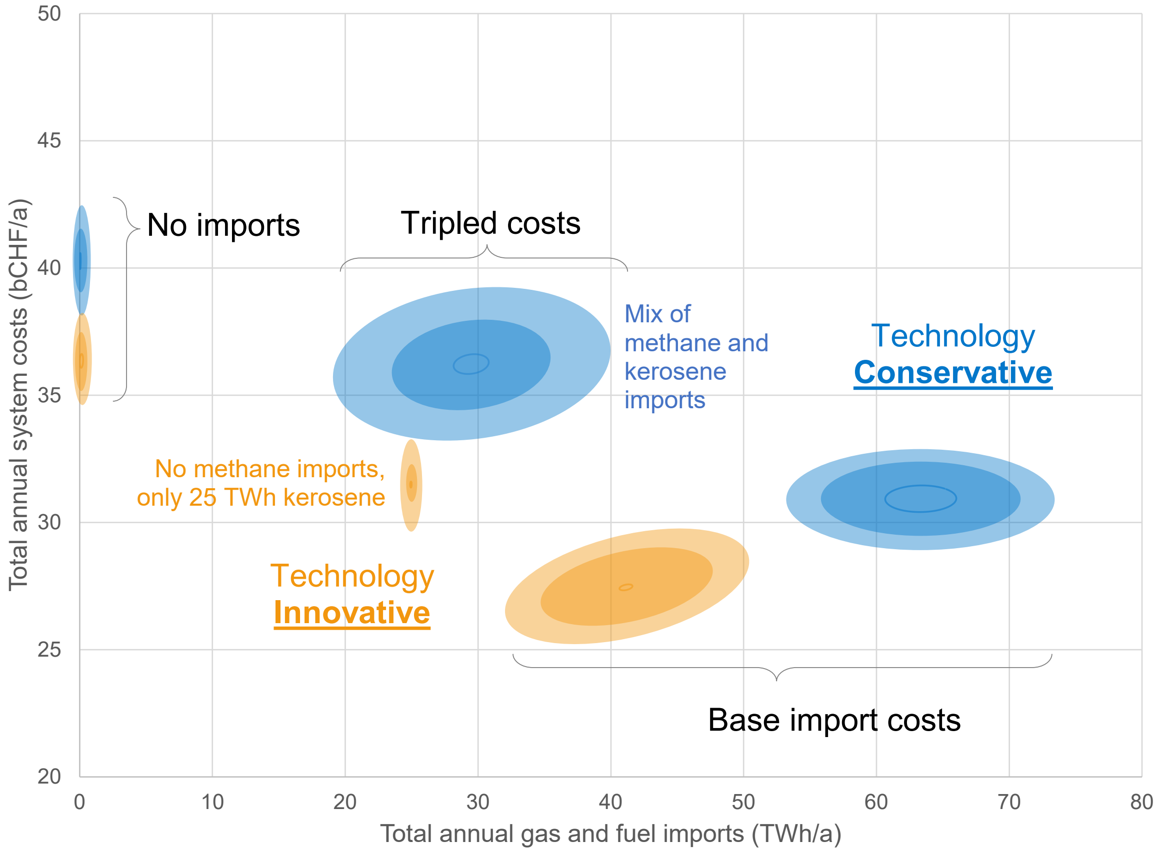

Figure 33: Trade-off between annual system costs and imports; no electricity imports; no B2X pathways.

The two basic scenarios, Conservative and Innovative, and their variants with tripled import prices for gases and fuels, and no imports are put in context in Figure 33, highlighting the trade-off between total system costs and the dependence on imports. Two conclusions can be drawn: (i) Reducing the dependence on gas and fuel imports has a high price, that is mostly paid for with oversized PV installations. (ii) Realizing the innovations that distinguish the Innovative from the Conservative scenario (see Table 2) has a doubly positive effect: it reduces both costs and imports considerably.

We did not explicitly model the import of sustainable, i.e., CO_2-neutral, aviation fuels (SAF). The results give, however, indications under which conditions such imports would be cost-optimal: as mentioned before, for baseline kerosene costs of 50-100 CHF/MWh, the cost-optimal strategy is to continue with fossil imports and to compensate with negative emissions from waste-to-energy plants, wood-CHP plants or DAC. The resulting supply costs of "sustainable" – i.e., compensated – fossil kerosene would be approx. 200 CHF/MWh (see Figure 34). If SAF would be available at a lower price, imports make economic sense, if they are more expensive, compensation is the better strategy. This limit of 200 CHF/MWh increases with higher kerosene costs; at three times the price it reaches approx. 300-400 CHF/MWh. Again, SAF costs below this value make imports attractive, above this value compensation is better.

If we decide not to import fossil kerosene, the domestic production costs would be 500-600 CHF/MWh. This is mainly due to the low capacity factors of wind and photovoltaic resources in Switzerland. Costs could be reduced to 400-500 CHF/MWh by increasing the selectivity of the Fischer-Tropsch process for kerosene. Such a strategy would only make economic sense if SAF import prices were above this value.

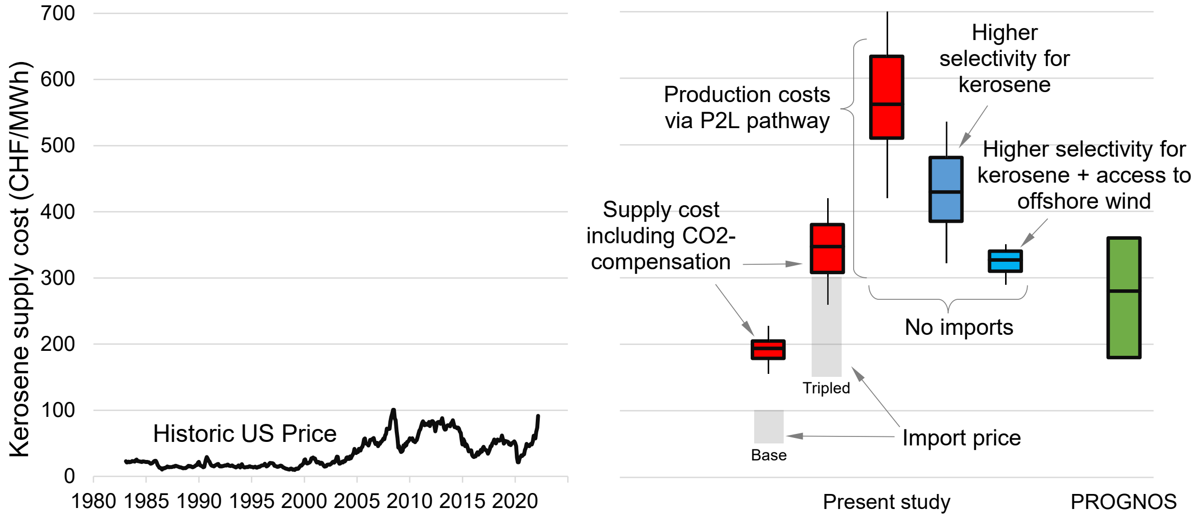

Figure 34: Historical and future kerosene supply costs, present study and results by PROGNOS [8].

This is however not very likely. The simple thought experiment in Section 4.7 showed that costs could be as low as 300 CHF/MWh if offshore wind resources were available. An even lower range of costs was estimated by PROGNOS in a recent project in Germany [8]. In a nutshell: as long as SAFs are expensive, Switzerland should import fossil kerosene and compensate with negative emissions. If SAF become economic, we should import them. Producing SAF in Switzerland is not a recommended strategy.

It must be stressed very clearly: the conclusions on P2X technologies relate to the specific conditions of Switzerland. None of our results invalidates the most likely decisive role that P2X technologies will play at a global level, be it to deliver hydrogen for power and heat generation or liquid fuels for aviation. While B2X technologies will also be important – especially to deliver negative emissions – they will suffer from all implications of biomass, e.g. land use, food competition, etc.

6 Recommendations

A number of recommendations follow from the work done in this project. These are partly specific to the field of synthetic gases and fuels and therefore of relevance for the upcoming SWEET call on sustainable fuels. However, since the energy system modelling with SES-ETH encompasses always all elements of the energy system, we use the occasion to also formulate some general recommendations that go beyond the narrow scope of the study.

Research priorities for synthetic gases and fuels:

- Research, development and demonstration in the field of synthetic gases and fuels is crucially important, not because Switzerland should build up large domestic production facilities but because the underlying technologies will be needed worldwide to tackle the challenge of completely decarbonizing the energy system – including aviation as the hardest part.
- The challenge of any Power-to-X (P2X) pathway is the need for large quantities of renewable electricity. Given the limitations of hydro power, such a P2X pathway must deal with the input from volatile renewable generation, mostly photovoltaics and wind. Low capacity factors are an inevitable feature of such power sources but generally not acceptable for a thermochemical process like the Fischer-Tropsch (FT) synthesis. Fully integrated systems must be developed and demonstrated that optimally combine electricity storage, electrolysis, hydrogen storage, CO_2 delivery (and possibly storage) and FT-synthesis, considering all time scales from hours to months. A simple model like SES-ETH has suggested a specific configuration, but this can only be a first starting point. Once configurations have been found, these should be fed back in simplified form to energy system models to update scenarios.
- Our analysis suggests that there is little benefit in producing Diesel as a by-product of kerosene. The decarbonisation of land-based mobility will pre-dominantly be electrical, and some non-electrical niches can be satisfied with hydrogen as primary fuel. Therefore, development of the FT-process in direction of a higher selectivity for kerosene is beneficial.
- Biomass-to-X pathways (B2X) are an important additional element in a net-zero scenario. They have inherent advantages over the P2X pathways, since they generally can run in baseload operation and they are able to deliver in addition negative CO_2 emissions. The drawback is the dependence on limited biomass resources. Here, B2X processes will compete with technologically less demanding alternatives such as wood combined heat and power (CHP) plants that can deliver heat to district heating networks or industrial processes. B2X technologies should be further developed and demonstrated at the Swiss scale, possibly with a range of secondary synthesis steps (WGS, methanation, RWGS+FT-synthesis) that can produce the full spectrum of synthetic gases and fuels.
- The work done here with SES-ETH considered the emissions of aviation and therefore showed ways how to reach a “true” net-zero. This is more ambitious than what was done before, both in the Energieperspektiven 2050+ and in the JASM project. Considering emissions from aviation must become the standard.

General recommendations can be formulated that are not specific to the question of synthetic gases and fuels but extremely relevant for reaching the Swiss net-zero emission goal:

- A Swiss CO_2-pipeline network is required to collect emissions from large point sources such as the 29 waste-to-energy plants, the 6 cement plants, the growing number of wood CHP plants and possibly smaller sources such as anaerobic digestion facilities (sewage sludge, green waste, manure, etc.). Our analysis suggests that having this infrastructure available will reduce the costs of decarbonization.
- We specifically defined a Conservative and an Innovative scenario to highlight the benefit of developing certain technologies. Realizing these innovations saves money and reduces the

dependency on imports of gases, fuels and electricity. The most important innovations are listed here:

- Building new hydro power plants in periglacial environments and increasing the reservoir volumes of regulated hydro power plants helps to increase winter electricity production.
- Photovoltaic generation cannot be limited to buildings. Rules have to be changed to allow for large scale facilities in rural environment (agri-photovoltaic) and in the mountains.
- Latest estimates of wind power show a larger potential than previously thought [28]. Wind power has two advantages over photovoltaics, generally a higher capacity factor and a higher production in winter. This potential must be exploited.
- Deep geothermal energy for direct heat usage in district heating networks, industrial processes and possibly CO_2-separation can have a huge positive impact on the energy system. The technology must be developed that allows for a safe extraction of geothermal heat.
- In a similar way, the use of the underground as seasonal thermal energy storage would have big advantages, especially by reducing the winter electricity demand of heat pumps that can then be operated in summer.
- A large potential, both for producing bio-methane and for generating negative CO_2 emissions, is present in the agricultural sector. Centralized digestion facilities need to be developed that collect agricultural residues from a larger radius. New technologies such as hydrothermal gasification, liquefaction or carbonization need to be put in practice.

Some elements of the energy transition – such as hydro power – are Swiss-specific and can be resolved by ourselves. Synthetic gases and fuels are not such a case since we have neither the proper renewable electricity resources nor sufficient biomass. Especially in the field of aviation fuels, the best strategy for Switzerland appears to be to compensate emissions as long as kerosene is mostly fossil and to import SAFs when they are available. Obviously, this is not a sustainable course of action for Europe or even the world – SAFs have to be produced somewhere, preferably in places that have the right resources. Switzerland should contribute to achieving this by focusing on its strengths in science and technology, bringing forward the technology of electrolysis, storage and fuel synthesis, and demonstrating it at industrial scale. This has to be done in cooperation with international partners.

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