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Prospective life-cycle assessment of greenhouse gas emissions of electricity-based mobility options

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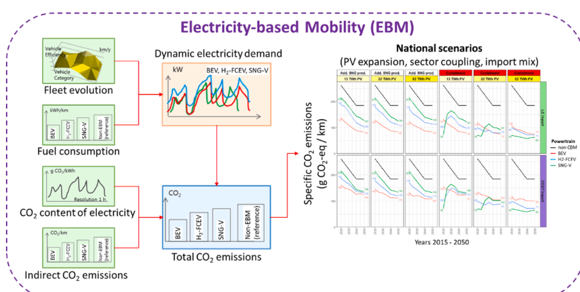
HIGHLIGHTS

- Electricity-based mobility (EBM) includes electricity-derived hydrogen and synthetic fuels.
- EBM allows for significant greenhouse gas (GHG) reduction compared to fossil fuels.
- With sector coupling, battery electric vehicle feature the lowest GHG emissions.
- Large PV expansion without sector coupling favors more flexible H_2 and SNG vehicles.
- Only a systemic view of GHG emissions allows for a fair comparison of EBM options.

GRAPHICAL ABSTRACT



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ABSTRACT

Electricity-based mobility (EBM) refers to vehicles that use electricity as their primary energy source either directly such as Battery Electric Vehicles (BEV) or indirectly such as hydrogen (H_2) driven Fuel Cell Electric Vehicles (FCEV) or Synthetic Natural Gas Vehicles (SNG-V). If low-carbon electricity is used, EBM has the potential to be more sustainable than conventional fossil-fuel based vehicles. While BEV feature the highest tank-to-wheel efficiency, electricity can only be stored for short durations in the energy system (e.g. via pumped-hydro storage or batteries), whereas H_2-FCEV and SNG-V have a lower tank-to-wheel efficiency due to additional conversion losses, H_2 and SNG can be stored longer in pressurized tanks or the natural gas grid. Thus, they feature more flexibility with regard to exploiting renewable electricity via seasonal storage. In this study, we examine whether and under what circumstances this additional flexibility of H_2 and SNG can be used to offset additional losses in the powertrain and conversion with respect to greenhouse gas (GHG) mitigation of EBM from a life-cycle point of view in a Swiss scenario setting. To this end, a supply chain model for EBM fuels is established in the context of an evolving Swiss and European electricity system along with an approach to estimate the penetration of EBM in a legislation compliant future passenger cars fleet. We show that EBM results in significantly lower life-cycle GHG emissions than a corresponding fossil fuels driven fleet. BEV generally entail the

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lowest GHG emissions if flexibility options can be offered through sector coupling, short-term and seasonal energy storage or demand side management. Otherwise, in particular with a large expansion of photovoltaics (PV) and curtailment of excess electricity, H_2-FCEV and SNG-V feature equal or – in case of high-carbon electricity imports – even lower GHG emissions than BEV.

Nomenclature

GHG	Greenhouse Gas (CO_2-eq)
CO_2-eq	CO_2 equivalent
NG	Natural Gas (from the grid)
SNG	Synthetic Natural Gas
CCS	Carbon Capture and Storage
EBM	Electricity Based Mobility
BEV	Battery Electric Vehicle
H_2-FCEV	Hydrogen Fuel Cell Electric Vehicle
SNG-V	SNG Vehicle
ICEV	Internal Combustion Engine Vehicle
HEV-p	Hybrid Electric Vehicle (petrol)
CH	Switzerland
EU	EU-28 (not including Estonia, Latvia, Lithuania)
LC	Low Carbon
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
CCGT	Combined Cycle Gas Turbine
SFOE	Swiss Federal Office of Energy (Bundesamt für Energie BFE)
PHS	Pumped-Hydro Storage
PV	Photovoltaics
ELYSE	Electrolysis
METH	Methanation
SMR	Steam Methane Reforming
EUSTEM	European Swiss TIMES Electricity Model
RNW_SOL	Renewable solar PV electricity generation
RNW_WIND	Renewablewind electricity generation
RNW_OTHERS	Other renewable electricity generation
RNW_GEO	Renewable geothermal electricity generation
RNW_CSP	Renewable Concentrated Solar Power electricity generation
RNW_TIDE	Renewable wave and tidal power electricity generation
STG_BAT	Stationary Battery
HYD_PUMP	Pumped-Hydro storage (PHS)
HYD_DAM	Hydro storage electricity generation
HYD_RUN	Run-of-the-River electricity generation
NUC	Nuclear electricity generation
GAS_CCS	Gas-fired electricity generation (with CCS)
GAS_B	Gas-fired electricity generation (Baseload)
OIL	Oil-fired electricity generation
COAL_CCS	Coal-fired electricity generation (with CCS)
COAL_B	Coal-fired electricity generation (Baseload)

1. Introduction

1.1. Motivation

In many countries - such as in Switzerland - the transport sector still emits one of the largest shares of greenhouse gas (GHG) emissions in the entire energy system [1–3]. An electricity-based mobility (EBM) with low life-cycle GHG emissions - along with other low environmental impacts - is one option to reduce GHG emissions by gradually substituting fossil fuels driven internal combustion engine vehicles (ICEV) [4,5]. Three promising EBM technologies are Battery Electric Vehicles (BEV), hydrogen (H_2) driven Fuel Cell Electric Vehicles (H_2-FCEV) and Synthetic Natural Gas Vehicles (SNG-V). All of these technologies use electricity directly or indirectly as their fuel: While BEV directly operate on electricity from the grid, H_2-FCEV and SNG-V indirectly use electricity as stored H_2 and SNG previously produced by electrolysis (ELYSE) and - in case of SNG - via a subsequent methanation (METH). Both BEV and H_2-FCEV feature an electric motor, which is fed with electricity from an on-board battery or fuel cell system, respectively, while SNG-V operate as conventional ICEV.

Each EBM technology features a different well-to-wheel efficiency (well-to-tank plus tank-to-wheel) and storability of their fuels [6]. While BEV feature a high tank-to-wheel efficiency [5,7,8], their energy demand can economically only be stored for short terms (hours to days). In turn, SNG-V have a lower well-to-wheel efficiency due to losses in the electricity conversion to SNG (well-to-tank) and the internal combustion based powertrain (tank-to-wheel). However, SNG can be stored for longer durations (seasons) in the existing natural gas (NG) grid or imported from a global scale [9]. Thus, SNG-V feature more flexibility with regard to the primary energy used to produce their fuel. Moreover, due to impending improvements (incl. hybridization) of ICEV, their tank-to-wheel efficiency may also increase [8,10,11]. On all of these grounds, SNG may become part of a wide-range of alternative fuels in mobility [12]. H_2-FCEV are between BEV and SNG-V both in terms of their well-to-wheel efficiency as well as in their storage flexibility (days to weeks). Eventually, H_2-FCEV are still in their infancy, therefore, substantial technological improvements can be expected [13,14].

For all EBM technologies, to feature systemic (i.e. regarding the whole energy system) low GHG emissions, renewable electricity with a low-carbon footprint must be used [7,15,16]. Conversely, if conventional thermal power plants (e.g. gas, coal or oil) are used to meet their additional electricity demand, no effective GHG mitigation will occur [8]. From a GHG mitigation point of view, the decisive factor are the GHG emissions per km travelled including all direct and indirect ("grey") GHG emissions from operation, fuel supply as well as manufacturing of the vehicles and other infrastructure (e.g. roads). Thus, the introduction of EBM must occur in parallel to an expansion of renewable electricity generation. However, in the near to mid-term future, it is unlikely that all electricity in Switzerland (and the EU) will stem from renewable sources [17]. Moreover, as many European countries phase out nuclear power, a gap of low-carbon baseload electricity must be filled [18,19]. Renewable electricity from hydropower is already well-exploited (in Switzerland), and hence difficult to increase, while the potential and exploitability of other intermittent and stochastic renewable technologies such as photovoltaics (PV) and/or wind are still vague [20,21]. As an alternative to increasing domestic renewable electricity supply, also importing more electricity from abroad is an option to fill this gap, however, then the imported electricity must feature a low GHG footprint [22].

In particular, renewable electricity from PV has a clear diurnal and seasonal pattern with peaks at noon and in summer, which generally do not match electricity demand peaks in the evening/morning and in winter, respectively. While diurnal discrepancies between demand and supply may be offset by local smart grids (e.g. demand side management) and well-connected grids with short-term electricity storage such as batteries and pumped-hydro storage (PHS), a sustainable energy system with high PV shares should in particular be able to cope with seasonal demand and supply discrepancies by adequate long-term (seasonal) storage. As seasonal storage of electricity with current technologies (e.g. PHS and batteries) is economically not sensible [23], it is still viable to store electricity seasonally by converting it to chemical energy carriers such as H_2 and SNG via power-to-X [24–27]. Despite its still relatively high costs and conversion losses, power-to-X is a promising option to promote and exploit the full potentials of PV, in particular with respect to mobility [28].

1.2. Literature review

Several studies have been conducted with regard to the environmental (e.g. GHG) life-cycle assessment (LCA) of EBM technologies, in particular BEV [11,14,29]. Other EBM technologies have also been investigated by Bauer et al. [7] in a novel LCA scenario analysis framework with conventional and hybrid ICEV as well as BEV and H_2-FCEV taking into account electricity as well as H_2 supply chains from fossil, nuclear and renewable sources. The H_2 supply chain for H_2-FCEV was further investigated by Wulf and Kaltschmid [30] for a broad variety of renewable and fossil H_2 production pathways. Building on the THELMA [5] and SCCER [31] projects, Cox et al. [8] and Infras [32] conducted attributional LCA studies (with global sensitivity and uncertainty analysis) on the environmental impacts of current and future passenger cars in Europe and Switzerland, respectively, including BEV, H_2-FCEV and SNG-V. All these studies known by the authors, however, have been performed on the vehicle technology level evaluating the environmental performance of single cars with given, static fuel (including electricity and H_2) supply chains.

To properly evaluate and compare the GHG mitigation potential of EBM in a systemic way, their different fuel supply chains have to be analyzed in a dynamic and evolving energy system. There are several studies with emphasis on such a systemic integration of EBM into the energy (electricity) system, however, they either do not have adequate temporal resolution to capture short-term dynamics (e.g. momentary demand and supply peaks) [33,34] or they investigate primarily BEV [35,36]. A Switzerland-specific study with an intra-annual hourly time resolution has been conducted by Kannan and Hirschberg [37]. They used the Swiss TIMES energy system model (STEM) [38] to investigate the interactions between the Swiss mobility (including BEV, H_2-FCEV, yet not SNG-V) and the electricity system in a technology-rich, cost-optimal modeling framework with a time horizon 2010 till 2100 for a conservative and a more ambitious decarbonization scenario. They also accounted for cross border electricity trading with neighboring countries and associated GHG contents of imported electricity by employing the CROSSTEM model [39]. They found that BEV support decarbonization of the car fleet even if electricity is supplied from large domestic gas power plants or relatively low-cost sources of imported electricity. They based their analysis on averaged hourly profiles for typical weekdays and weekends in three seasons (summer, winter, and intermediate season). However, they did not account for the entire life cycles of vehicles, fuel supply, and related infrastructure. In a more recent study, Blanco et al. [40] conduced an ex-post LCA of power-to-methane based on results from the JRC-EU-TIMES energy system model covering five energy sectors, 18 impact categories and 31 European countries. However, to the best of our knowledge, LCA-based quantification of impacts on climate change of different vehicle options in a systemic context, i.e. considering their impact on and interrelation with the electricity sector, has not been performed; neither for Switzerland, nor for a larger geographical scope.

The novelty of this study is to combine methods and models from Kannan and Hirschberg [37], Bauer et al. [41], Cox et al. [8] as well as Pareschi et al. [42] to investigate all three EBM powertrains (BEV, H2-FCEV and SNG-V) both from an LCA and energy system integration point of view. To this end, a novel EBM fuel supply chain model is set up in order to explicitly evaluate how the greater flexibility (storability) of gaseous fuels of H2-FCEV and SNG-V can leverage GHG mitigation compared to a BEV only fleet in a future Swiss and European energy system (beyond Switzerland's neighboring countries) with a large deployment of renewables (in particular PV). In this respect, in particular the impact of curtailment of renewable electricity due to a diurnal and seasonal mismatch of demand and supply is addressed and related to the primary research question of how and under what circumstances the selective use of low-carbon electricity and subsequent enhanced storability (flexibility) of H_2 and SNG can offset this seasonal mismatch despite additional energy losses associated with H_2-FCEV and SNG-V compared to more efficient but less flexible BEV or fossil fuels based ICEV powertrains.

To answer these research questions 1) the evolution of EBM powertrains and their hourly end-energy demand in the Swiss passenger cars fleet is modelled such that legislative CO_2 emission targets are fulfilled, 2) the evolution of the Swiss and European electricity generation mix and associated GHG emissions are modelled based on Swiss and European energy strategies as well as 3) life-cycle GHG emissions of individual generation technologies such that 4) EBM powertrains and their fuel supply chain can be modelled dynamically with respect to demand, supply and storage at an hourly time resolution to 5) effectively reduce GHG emissions in the entire energy system from a life-cycle perspective.

1.3. Scope and structure

As many countries aim at decarbonizing their energy systems by massively increasing the fleet of BEV, this study, provides decision makers with a solid, data-based foundation to compare the effective GHG mitigation potential of different EBM powertrain options depending on specific boundary conditions of the respective energy system such as renewable energy deployment, GHG content of imported electricity and potential for sector coupling (i.e. avoidance of curtailment).

This study primarily investigates technological and physical aspects of EBM in the Swiss energy system at a nationally aggregated level. Results may, however, readily be generalized for other countries with similar energy systems. Socio-economic aspects as well as fuel supply chain aspects on both a global and regional scale, although also of high relevance, are out of the scope of this study.

This study is structured as follows: In Chapter 2, the models used to answer the above mentioned research questions are presented. This includes a disclosure and discussion of all assumptions and input parameters/profiles pertaining to the models. Additional information on the data and models are provided in "supplementary materials". Chapter 3 presents the main results of the study: 1) with respect to the evolution of the EBM fleet and its end-energy demand, 2) the different pathways to supply energy for this EBM fleet, 3) implications on the energy system and 4) with respect to systemic and specific GHG mitigation. A discussion of these results including a section on their applied value as well as an outlook for further study is included in Chapter 3. In Chapter 4, the main findings of the study are summarized.

2. Methodology

In this study, several models are combined to assess the specific GHG emissions of EBM powertrains. All models are applied to the same four powertrain scenarios: Three EBM scenarios, in which a certain share of the future Swiss passenger car fleet is substituted by either BEV, H2-FCEV, or SNG-V; and a fourth reference "non-EBM" scenario, in which no substitution occurs instead the corresponding share remains gasoline and diesel ICEV driven. In this case, the legislative targets for average GHG emissions of newly registered passenger cars cannot be fulfilled. This "non-EBM" scenario is used to benchmark the GHG mitigation potential of EBM against a reference fossil fuels based mobility.

Fig. 1 provides an overview of these models including their connections as well as inputs and outputs. In the following sections and supplementary materials (S), these models are described in more detail. In short, by means of the simplified stock-flow cohort model (see Sections 2.1, S.5.1 and S.5.2.1), the evolution of a legislation compliant Swiss EBM passenger cars fleet is modelled. The annual and hourly fuel demand of this EBM fleet is calculated by means of their specific tank-to-wheel (TTW) consumptions and a "Direct Use of Observed Activity-Travel Schedules" (DUOATS) model. The evolution of the Swiss and European electricity supply mix is obtained from the EUSTEM least-cost optimization (see Sections 2.2, S.2 and S.6). Specific life-cycle (LCA) GHG emissions of electricity generation and EBM powertrains are taken from the ecoinvent database (see Section 2.4 and S.7). Eventually, the hourly GHG content of the used EBM fuels (incl. electricity) are calculated by means of the EBM fuel supply chain model (see Sections 2.3, S.1, S.3 and S.4) to yield the specific GHG emissions of each EBM powertrain for each investigated scenario with respect to domestic PV expansion, import electricity GHG content and potential for sector coupling (i.e. curtailment avoidance).

2.1. Fleet evolution and energy demand of EBM powertrains

The annual end-energy (fuel) demand of each EBM powertrain (BEV, H_2-FCEV, SNG-V) is estimated based on the evolution of their tank-to-wheel consumption [8] and their penetration in the future Swiss passenger cars fleet. To this end, a fleet evolution scenario is established, in which each EBM powertrain is individually introduced such that Switzerland's current and foreseeable future targets for average CO_2 emissions of newly registered passenger cars are fulfilled. The fleet then evolves following a simplified stock-flow cohort model in which all vehicles are scrapped or exported, when they reach the age of 15 years [43].

For the sake of simplicity, no plug-in versions of H_2-FCEV and SNG-V are included. Likewise, no distinction in terms of car market segments is made. Moreover, only one EBM powertrain is introduced into the fleet and the other two are excluded from that scenario. Only passenger cars are considered. Novel aspects of mobility such as vehicle sharing or autonomous driving are neither taken into account.

For more details on these models and their underlying assumptions, refer to section S.5 in the supplementary materials.

2.2. Evolution of Swiss and European electricity generation mix

To obtain the long-term evolution of electricity generation technologies both in Switzerland and the EU, the technology-rich, bottom-up, least-cost optimization model EUSTEM (European Swiss TIMES electricity model) is employed [44,45]. EUSTEM optimizes for potential pathways to decarbonize the electricity sector in accordance with national energy policies (e.g. phase-out of nuclear and coal power plants), renewable energy targets, and trends of development of future power generation and transmission systems. Decarbonization follows the ambitious European low-carbon (LC) target: Total direct GHG emissions are reduced by 80% until 2050 compared to 1990 levels. This is translated to a reduction in GHG emissions from the electricity sector of 32% by 2020, 60% by 2030, and 95% by 2050. This includes a large expansion of renewable electricity generation technologies along with carbon capture and storage (CCS) with fossil power plants (e.g. gas and coal).

For more details on the employment of the EUSTEM model in this study and its underlying assumptions, refer to section S.6 in the supplementary materials.

2.3. Supply chain model of EBM fuels

2.3.1. Model scheme

To model the supply chain of EBM fuels at an hourly time resolution with respect to GHG emissions, the "open energy modeling framework" (oemof) is used [46]. Oemof is a mixed-integer-linear-programming (MILP) tool to flexibly describe energy systems as a graph of nodes, edges, and buses. In a bus, all input and output flows must be balanced at any time. A schematic representation of this fuel supply chain model as implemented in oemof is shown in Fig. 2.

The fuel supply chain model is composed of three buses: an electricity, H_2 and SNG bus. Inflows to these three buses come from various electricity supply sources in Switzerland and abroad (import) as well as from the natural gas (NG) grid. Sinks are the base electricity demand, the exported electricity and the end-energy (fuel) demand of BEV, H_2-FCEV and SNG-V. Moreover, there is a slack excess electricity node, from which excess electricity is either converted to additional SNG via electrolysis (ELYSE) and methanation (METH) for use in other energy sectors (e.g. heavy-duty transportation, process heat, chemicals, etc.) or - as

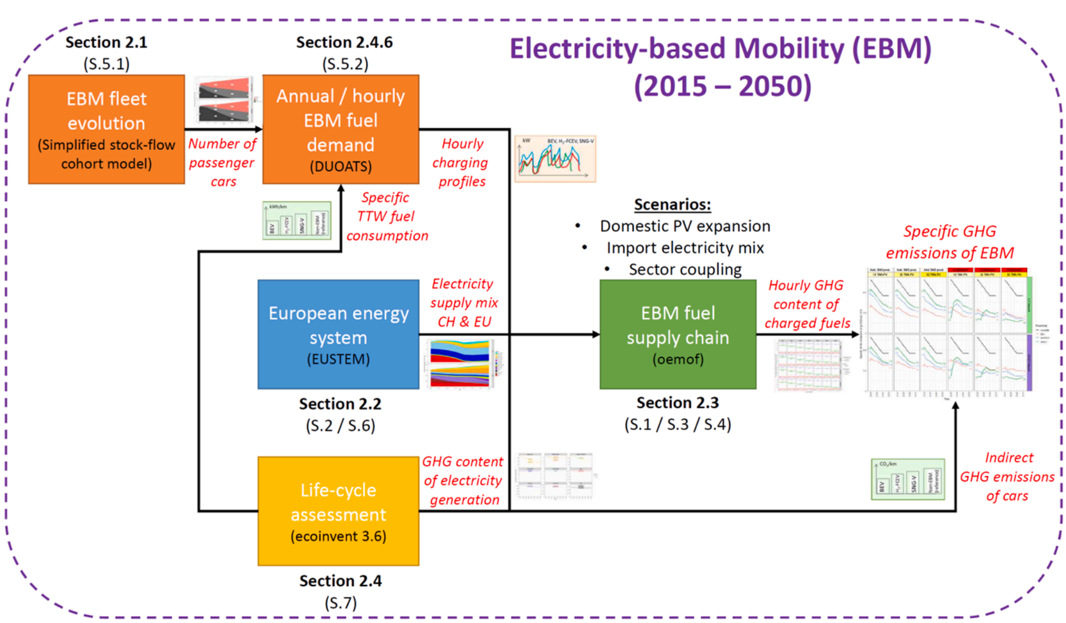

Fig. 1. Overview of the models (modules) used in this study to investigate the specific GHG emissions of EBM powertrains (including their respective inputs / outputs).

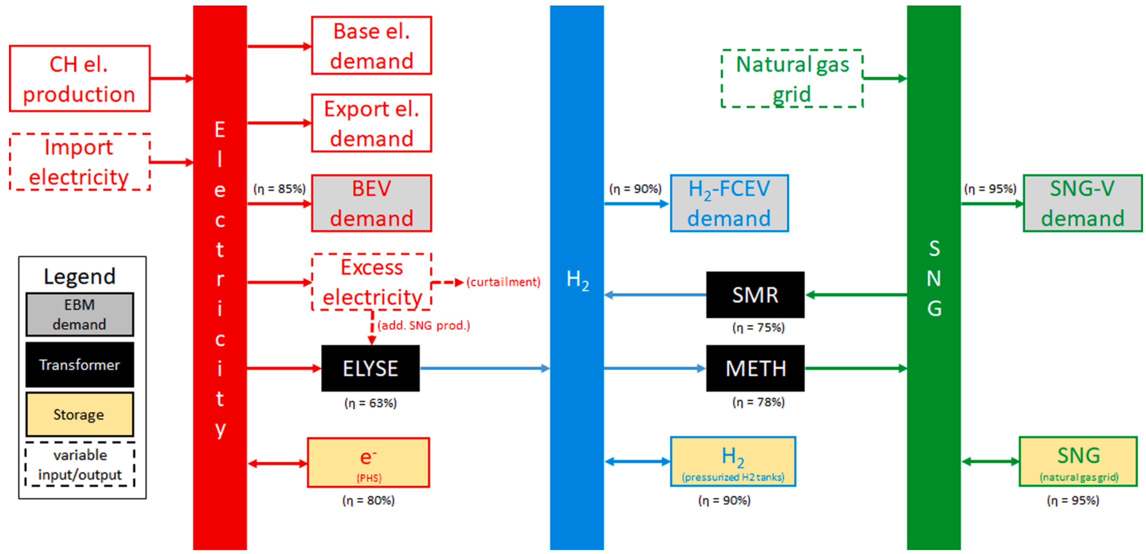

Fig. 2. Scheme of the model used to investigate the supply chain of EBM fuels with respect to GHG emissions.

a last resort - curtailed. Besides the route via ELYSE, H_2 can also be produced from synthetic and grid NG via steam methane reforming (SMR). However, re-electrification of H_2 or SNG is not possible due to economic and regulatory reasons [28]. All buses are linked to storage nodes, namely, pumped-hydro storage (PHS), pressurized H_2 tanks, and the existing NG grid.

In the following, all inputs and outputs as well as other characteristics (e.g. constraints and boundary conditions) of the model in Fig. 2 are described (for more details refer to the supplementary materials).

2.3.2. *Electricity supply*

2.3.2.1. General. Electricity can be supplied either from domestic generation or imports. While domestic generation is a fixed input, imports are modelled as a slack variable to balance - along with grid NG - all supply and demand, while minimizing systemic GHG emissions subject to all constraints in the model of Fig. 2.

2.3.2.2. Hourly profiles. The composition of the domestic (CH) and imported (EU) electricity mix is obtained from the EUSTEM model and its low-carbon (LC) decarbonization scenario for the years 2015 to 2050

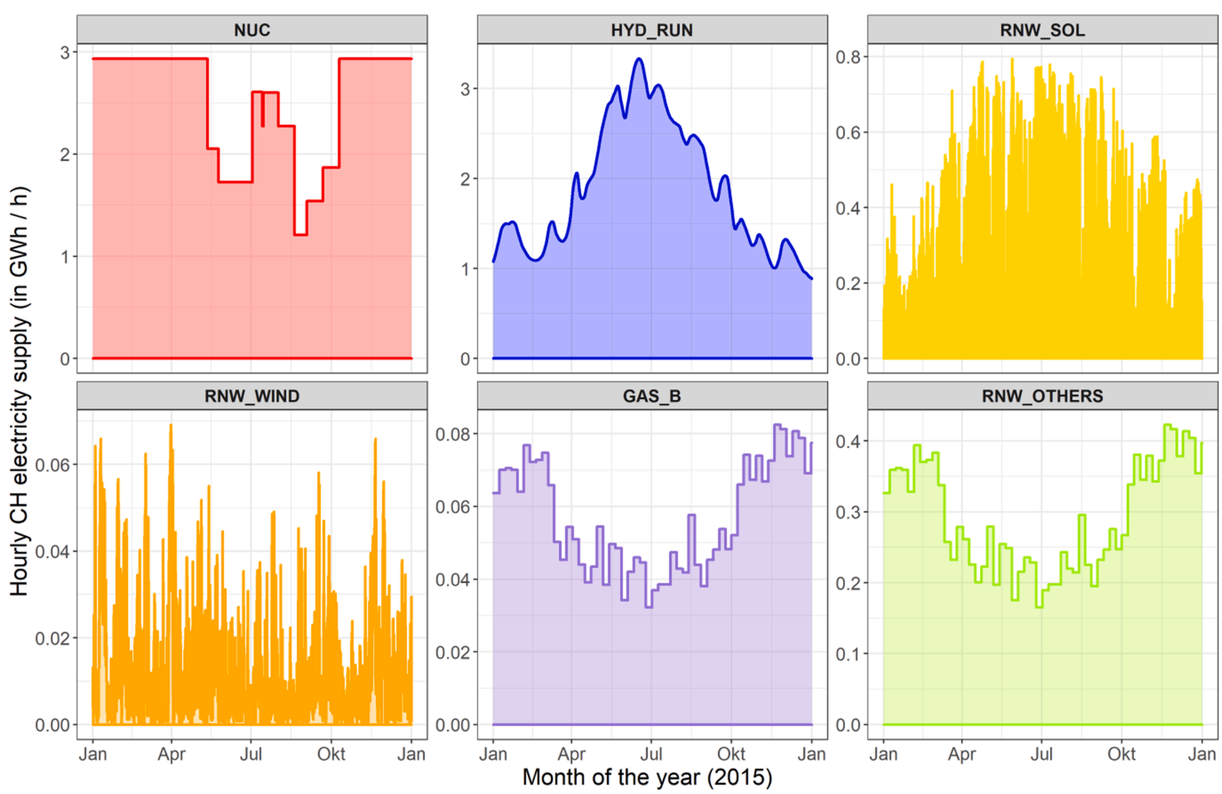

Fig. 3. Actual hourly electricity supply of inflexible electricity generation technologies in the reference year 2015, which is linearly scaled to the annual supply of EUSTEM-LC for the years 2015 to 2050 (see supplementary materials for more details).

(see Section 2.2). This CH and EU supply mix is the reference to obtain the hourly supply profiles in the non-EBM, H_2-FCEV and SNG-V scenarios. For the BEV scenario, a corresponding supply mix with an additional BEV electricity demand in CH is modelled with EUSTEM-LC.

Hourly profiles of the EU supply mix are available for typical (average) days in each season. For domestic generation, actual hourly generation profiles of 2015 are used for each technology as reference (see Fig. 3) and then linearly scaled to the annual electricity supply obtained from EUSTEM-LC for all years 2015 to 2050:

- **Nuclear** (NUC) supply is based on availability and generation data of Swissnuclear [47] and SFOE [48] (see section S.1.1 in the supplementary materials for more details).
- **Wind** (RNW_WIND) and **PV** (RNW_SOL) generation profiles are based on hourly capacity factors in Switzerland from "renewables.ninja" [49] (see sections S.1.2 and S.2.2 in the supplementary materials for more details, respectively). For PV, two additional exogenous PV expansion scenarios in CH are introduced (see section 2.3.2.3).
- **Run-of-river** (HYD_RUN) and **conventional-thermal** generation (GAS_B and RNW_OTHERS) are derived from reported Wednesday and annual production sums of SFOE [48] (see sections S.1.4 and S.1.5 in the supplementary materials for more details, respectively).
- For the flexible part of **storage** (HYD_DAM) and **pumped-hydro storage** (PHS) generation a separate dispatch model based on the residual load as a proxy for electricity prices on the market is used (see section S.1.5 in the supplementary materials for more details)

2.3.2.3. Exogenous PV expansion scenarios. In addition to the annual domestic PV supply provided by the least-cost optimization of EUSTEM-LC of 13 TWh by 2050, two exogenous PV expansion scenarios with a 2.5- and 4-times larger PV supply are included to investigate the influence of a higher PV expansion in Switzerland. By 2050, these two exogenous PV expansion scenarios yield 32 TWh and 52 TWh (see Fig. S-1 in the supplementary materials). The 32 TWh scenario emulates the PV expansion envisioned by Prognos et al. [50] and the 52 TWh scenario corresponds to the reported maximum domestic PV potential on suitable rooftops by "sonnendach.ch" [51,52]. In these two exogenous PV scenarios, the annual supply of all other CH and EU electricity generation technologies to meet the domestic demand remains unchanged as provided by EUSTEM-LC.

It must be noted that these two additional exogenous PV scenarios are not based on any least-cost optimization such as the 13 TWh scenario obtained from EUSTEM-LC. This approach is, however, in line with Jochem et al. [53] who claim that renewable power plants (such as PV) are constructed neither due to economic reasons alone, nor because of a strategically good allocation in terms of the electricity demand, but rather because of regulations, politics, and regional potentials.

2.3.3. Natural gas supply

Natural gas (NG) from the grid is used as an additional energy source in the model to fuel SNG-V and H_2-FCEV (via SMR), if its impact on the overall (systemic) GHG emissions is less than using electricity (via ELYSE and METH). This may occur if the GHG content of electricity is higher than the one of grid NG, which is especially the case if grid NG contains a substantial share of low-carbon biomethane (see Section 2.4.3). Taking into account conversion efficiencies, this threshold is substantially lower for SNG-V than for H_2-FCEV.

2.3.4. Base electricity demand

The base electricity demand is the end-use electricity demand (including losses) in Switzerland without the additional demand of EBM and pumped-hydro storage (PHS) pumps. The end-use electricity demand (without losses) in the control block Switzerland is reported at a quarter-hourly time resolution by the Swiss TSO Swissgrid [54]. In 2015, this end-use electricity demand was 56.8 TWh. In order to be at a consistent temporal resolution with other datasets, this data is aggregated to an hourly time scale. Next, the hourly profile is linearly scaled to the annual electricity demand (including losses) from 2015 (61.1 TWh) to 2050 (66.3 TWh) based on the "business-as-usual" (BAU) scenario of Prognos [55] (see Fig. S-7 in the supplementary materials).

2.3.5. Hourly EBM end-energy demand

The hourly end-energy demand of each EBM powertrain (BEV, H_2-FCEV, SNG-V) is derived from its annual end-energy demand as well as the Swiss mobility survey "Mikrozensus Mobilität und Verkehr (MZMV)" [56] and the "Direct Use of Observed Activity-Travel Schedules" (DUOATS) methodology described in Pareschi et al. [42]. For more information on this derivation, refer to section 2.1 and S.5 in the supplementary materials. These hourly recharging / refueling profiles are implemented as sinks in the model in Fig. 2. Along with the conversion efficiencies of the transformers ELYSE, METH and SMR (see section 2.3.7), the resulting electricity demand of each EBM powertrain is obtained.

2.3.6. Exported electricity

The exported electricity from Switzerland is modelled as an additional sink (demand) in the model in Fig. 2. It is taken as the net export of the EUSTEM-LC least-cost optimization. Net exports are the positive hourly differences of the gross exports minus the gross imports in each hour of each typical (average) day per year and season. No distinction between weekdays and weekends is made. In the fuel supply chain model only net exports are set a-priori as a fixed input (demand) from EUSTEM-LC, net imports are modelled dynamically as a slack variable for every hour of the year within the oemof optimization for least systemic GHG emissions. Hourly profiles of these net exports (along with the corresponding gross exports and imports from EUSTEM-LC) can be seen in Fig. S-2 in the supplementary materials.

2.3.7. Energy conversion technologies

The overall efficiencies based on the LHV of the conversion technologies ELYSE, METH and SMR are 57%, 47% and 65%, respectively. These overall efficiencies include the net conversion efficiencies and compression efficiencies of 90% and 95% for H_2 (700 bar) and SNG (250 bar), respectively. The installed capacities (in GW) are the annual maximum hourly excess electricity (for ELYSE and METH) and the annual maximum hourly H_2 demand of H_2-FCEV (for SMR).

For more details on these conversion efficiencies and installed capacities, refer to section S.3 in the supplementary materials.

2.3.8. Energy storage

The energy storage technologies implemented in the model in Fig. 2 are 1) pumped-hydro storage (PHS) for short-term (hours to days) electricity storage (80% round-trip efficiency, 3.76 GW charging/discharging power, yearly-varying storage capacity based on maximum daily excess electricity), 2) pressurized tanks for short- to medium-term (days to weeks) H_2 storage (90% round-trip efficiency, unlimited charging/discharging power, yearly-varying maximum daily H_2 demand as storage capacity) and 3) the existing NG grid for long-term (seasonal) SNG storage (95% round-trip efficiency, unlimited charging/discharging power and storage capacity). The NG grid is also an option for seasonal H_2 storage by converting H_2 to SNG via METH (typically in summer) and seasonally storing it for later reconversion to H_2 via SMR (typically in winter), if this route features lower GHG emissions than H_2 production via ELYSE and short- to medium-term storage in pressurized tanks. All these storage technologies are implemented such that their storage level must be at 50% of their storage capacity at the beginning and end of each year. For more details, refer to the supplementary materials.

2.3.9. Excess electricity

Excess electricity occurs if the momentary inflexible electricity supply is larger than the momentary inflexible electricity demand. Inflexible electricity supply includes all technologies except for pumped-hydro storage (PHS) and hydro storage power plants, while inflexible electricity demand includes all demands (including BEV) except for PHS pumps and ELYSE.

There are two extreme cases how excess electricity is treated in all EBM scenarios in the model in Fig. 2:

1. Preferably all excess electricity is used in other energy sectors (e.g. heavy-duty transportation, industry, chemicals, etc.). As a proxy for this situation, an additional SNG production via ELYSE-METH is included in the model. It must be noted that this additional demand of SNG in other energy sectors is not explicitly modelled, it is just presumed that it may be used elsewhere and only the amounts of excess electricity and thereof producible SNG are quantified.
2. As a last resort, all excess electricity is curtailed. This is the least favorable option with respect to excess electricity, as it is not desirable both from an economic and ecological point of view [57].

In reality, most likely a situation between these two extreme cases will (at least temporarily) occur.

The additional export of excess electricity is not allowed since it is assumed that in a future European energy system with a large and ubiquitous generation from PV and wind, situations of excess electricity will occur simultaneously due to similar *trans*-continental weather (climate) situations as well as limited transmission capacities [58]. This *trans*-continental situation of excess electricity from renewables temporarily occurs already now as negative electricity prices on the markets suggest [59,60].

Additional short-term electricity storage with PHS and new batteries (incl. vehicles-to-grid) is not considered as an option, because a substantial proportion of the overproduction is seasonal [19]. Thus, storing and shifting additional noon excess electricity to evening/night hours would only slightly alleviate the situation as there is not enough overall electricity demand in summer to substantially consume large amounts of excess electricity [61]. Moreover, with current technologies, seasonal electricity storage is neither an economically nor ecologically viable option [28].

2.4. Life cycle assessment of electricity, fuels and vehicles

2.4.1. General

In this section, LCA based, specific GHG emissions of different fuel supply and vehicle technologies (including vehicle production and infrastructure requirements) are provided, considering all stages of the specific life cycles, i.e. production, use, and end-of-life. In this respect, fuel supply does not only concern electricity produced in Switzerland and abroad, but also conventional natural gas, gasoline and diesel, H_2 and SNG. These GHG emission factors are based on previous analysis [8,26,41,62] as well as the ecoinvent LCA database (version 3.6) [63].

2.4.2. GHG content of electricity

2.4.2.1. GHG intensities. GHG intensities are expressed in units of kg of CO_2 equivalents (CO_2-eq) per kWh of electricity produced at the power plants from an LCA perspective. GHG emissions are quantified using global warming potentials for a time horizon of 100 years according to IPCC [64]. For the years 2015 and 2020, GHG intensities are estimated based on the ecoinvent database. The system model "allocation, cut-off by classification" is used. In this system model, recommended for attributional LCA, environmental burdens related to recycling processes are allocated to the user of the secondary materials and scrap materials are free of environmental burdens. For 2025 to 2050 extrapolations considering expected future technology development according to Bauer et al. [41] are performed. These specific GHG intensities of electricity generation technologies abroad (EU) and in Switzerland (CH) from 2015 to 2050 are shown in the supplementary materials in Table S2.

2.4.2.2. Imported electricity. Since, according to Rüdisüli et al. [19], the GHG content of imported electricity is the single most influential factor regarding the GHG content of electricity used in Switzerland, this influence is estimated by means of two (extreme) scenarios:

1. **"LC":** In this scenario, the hourly GHG content of imported electricity is equal to the GHG intensity of the average electricity supply mix in EUSTEM's low-carbon (LC) scenario (see section 2.2) with a substantial share of renewables and fossil power plants with CCS. In other words, there is a common market for electricity in the EU, while Switzerland can only import electricity from all EU countries simultaneously and proportionally to their overall production. This overall EU production is provided by EUSTEM at an hourly time resolution for typical (average) days with respect to seasons and weekdays for the years 2015 to 2050. Thus, the hourly GHG content is only calculated for such typical days. This means the actual daily and hourly dynamics of volatile renewables such as PV and wind are averaged out. Nonetheless, this averaged GHG content in each hour of these typical days features typical production patterns of these volatile renewables with a high production in summer at noon for PV and higher production for wind in winter (during the whole day).
2. **"CCGT":** This exogenously defined scenario presumes that only electricity from combined-cycle-gas-turbine (CCGT) power plants can be imported. This is in line with Rüdisüli et al. [19] and can be regarded as the "best fossil case" of imports. The specific GHG content of "CCGT" is assumed to be constant throughout the year, yet will decrease from 423 g CO_2-eq / kWh (in 2015) to 360 g CO_2-eq / kWh (in 2050). Moreover, this CCGT scenario is in line with the paradigm that the additional (marginal) electricity demand of EBM must be meet by additional, typically fossil (e.g. coal, gas, oil, etc.) power plants in the merit order [22,53,65] or any other (least-cost) unit commitment scheme. Last but not least, this CCGT scenario also reflects the variant in Prognos [55] to build new Swiss CCGT instead of importing electricity.

2.4.3. Natural gas from the grid

The GHG content of natural gas (NG) from the grid depends on the admixture of biomethane. In 2020, the biomethane content in the NG grid was about 20% [66]. According to the Association of the Swiss Gas Industry (VSG), they plan to be "CO_2 neutral" by 2050 [66]. To be on the conservative side, we assume a linear increase of biomethane in the NG grid from 20% in 2020 to 50% by 2050.

The GHG intensity of fossil NG is 239 g CO_2-eq / kWh_{th}, whereof 203 g CO_2-eq / kWh_{th} stem directly from the combustion [63,67]. For biomethane, the combustion is regarded "CO_2 neutral" (0 g CO_2-eq / kWh_{th}), however, the pre-processing of biomethane accounts for about 61 g CO_2-eq / kWh_{th} [68]. Hence, in 2020 with a share of 20% biomethane, grid NG features 203 g CO_2-eq / kWh_{th}, which linearly decreases to 150 g CO_2-eq / kWh_{th} by 2050 (see Table 1). Alternatively, an increased admixture of H_2 and SNG from foreign sources is justifiable.

Table 1
Evolution of mixture of fossil and biomethane in the natural gas (NG) grid and resulting life-cycle GHG intensity of natural gas.

Mixture	GHG intensity	2015	2020	2030	2040	2050
Biomethane	61	15%	20%	30%	40%	50%
Fossil NG	239	85%	80%	70%	60%	50%
Grid NG	g CO2-eq / kWh_{th}	212	203	186	168	150

2.4.4. GHG footprint of conversion technologies

Associated life-cycle GHG emissions to build, operate and discard ELYSE and METH infrastructure are included in the indirect GHG emissions of the corresponding H_2-FCEV and SNG-V powertrains (see Section 2.4.5) provided by Cox and Bauer [69] and Zhang et al. [26,62]. In this analysis, METH is fed with CO_2 captured from ambient air ("Direct Air Capture"). This assumption reduces complexity, as multi-functionality of processes generating CO_2 feedstock do not need to be taken into account [26,70].

For SMR, to produce H_2 from NG, indirect GHG emissions of 50 g CO_2-eq / kWh_{H2} are assumed according to Antonini et al. [71]. These indirect GHG emissions of SMR are assumed to stay constant over time. In turn, for the used NG, the GHG intensity from above with increasing amounts of added biomethane are taken.

2.4.5. GHG emissions of fossil and EBM powertrains

Direct and indirect GHG emissions associated with EBM and fossil powertrains are taken from the LCA study of current and future passenger cars in Switzerland of Cox and Bauer [69], which build upon the analysis of Cox et al. [8].

The specific LCA (direct and indirect) GHG emissions of fossil ICEV linearly decrease between 2018 and 2040 from 294 to 195 g CO_2-eq / km for gasoline and from 234 to 167 g CO_2-eq / km for diesel, respectively. This reduction is due to more efficient powertrains, light weighting and mild hybridization. Before 2018 and after 2040, GHG emissions are for the sake of simplicity assumed to remain constant in order to be in line with an anticipated S-shaped curve of technology improvements.

For the EBM powertrains BEV, H_2-FCEV and SNG-V only indirect GHG emissions are needed, as the fuel related GHG emissions associated with their primary fuel "electricity" are calculated within the model in Fig. 2. These indirect GHG emissions of EBM include - amongst others - the construction of the vehicle, on-board fuel storage (e.g. batteries, pressurized H_2 and SNG tanks, etc.) as well as any other infrastructure such as ELYSE and METH plants. For more information on these indirect GHG emissions of EBM, refer to Cox et al. [8,69] and Zhang et al. [26]. The evolution of these indirect GHG emissions of powertrains from 2015 to 2050 is listed in Table 2.

2.5. Systemic and specific GHG emissions

The impacts of EBM on GHG emissions in the energy system (including both the electricity and NG grid) is investigated both with respect to overall (systemic) GHG emissions (in Mt CO_2-eq / year) and specific GHG emissions (in g CO_2-eq / km travelled). While, the overall GHG emissions are obtained by summing all direct and indirect GHG emissions in the model in Fig. 2 over one year, specific GHG emissions of EBM are obtained by means of a short-term marginal electricity mix approach. This approach assigns all additional GHG emissions to meet an additional (marginal) demand to that additional consumer (e.g. BEV). In other words, it refers to the rate at which GHG emissions would change with a small change in the energy demand [72]. This implies running the model twice; once with and once without that additional demand and then calculating the differences in terms of GHG emissions. Despite its intuitive and differentiated accounting of additionally consumed renewable energy, which could otherwise also be used elsewhere to reduce fossil energy [65], the notion of "additional" demand and "marginal" GHG emissions may be controversial [73,74], as a proper definition and ranking of "additional" energy demands (in particular if there are several such as from transport and heating, etc.) may be ambiguous.

Table 2
Assumed evolution of the indirect ("grey") GHG emissions of EBM powertrains (in g CO_2-eq / km) from 2015 to 2050 based on Cox and Bauer [69]. As a comparison, also the indirect and overall (direct + indirect) GHG emissions of a reference ("non-EBM") fleet with 60% gasoline and 40% diesel vehicles are listed.

Powertrain	GHG emissions	2015	2020	2030	2040	2050
BEV	indirect	89	87	77	67	67
H2-FCEV	indirect	102	99	85	71	71
SNG-V	indirect	71	70	64	58	58
non-EBM	indirect	94	91	78	65	65
	direct + indirect	270	262	223	184	184

3. Results and discussion

3.1. EBM penetration and annual end-energy demands

The evolution of conventional ICEV (including 48 V hybrids) and Hybrid Electric Vehicles (HEV-p) as well as novel EBM powertrains in the fleet of newly registered and total Swiss passenger cars is displayed in Fig. 4. In the reference scenario "non-EBM", the red area in Fig. 4 remains fossil fuels driven with 60% gasoline and 40% diesel ICEV. As stipulated, all fossil fuels driven ICEV exit the market of newly registered passenger cars by 2040, while the share of EBM and HEV-p gradually increases to 70% and 30% in the market by 2050, respectively. As a result, the stock of EBM powertrains in the total fleet increases approximately linearly up to 58% by 2050, while the rest of vehicles is expected to decrease to 39% HEV-p and 4% ICEV (all converted to 48 V hybrids). The overall fleet size grows to reflect the prognosis of the Swiss transportation outlook [75].

Based on this penetration of EBM in the total stock of moving passenger cars and the specific powertrain tank-to-wheel (TTW) consumptions of each EBM from section 2.1, the annual end-energy demand of BEV, H_2-FCEV and SNG-V is obtained as 7 TWh of charged electricity (including charging losses), 10 TWh of H_2 and 18 TWh of SNG by 2050 (see Table 3). As a reference, the total end-energy consumptions of electricity and natural gas in Switzerland in 2017 was 58 TWh and 33 TWh, respectively [76]. The corresponding source and demand of electricity - and natural gas - is discussed in the next section.

The resulting hourly recharging / refueling profile is shown and described in the supplementary materials (section S.5.2.2) for an exemplary weekly of all EBM powertrains. The corresponding hourly electricity demand can also be found in section S.9 of the supplementary materials.

3.2. Annual fuel supply and electricity demand of EBM

3.2.1. BEV

Fig. 5 shows the amount and origin of electricity needed to meet the demand of BEV in all PV (13 TWh, 32 TWh, and 52 TWh) and import GHG scenarios (LC and CCGT). All electricity either stems from additional imports or from domestic (excess) electricity. Both sources can increasingly be exploited by using short-term electricity storage (i.e. PHS) to shift them to the actual hours of BEV demand. With LC imports and 13 TWh PV, mainly import electricity (5.6 TWh, including PHS losses[1]) is used, whereof 1.1 TWh are shifted by means of PHS in 2050. These 5.6 TWh correspond to about 10% of the current Swiss end-use electricity demand of about 57 TWh [77]. With more PV in Switzerland and LC imports, it is an increasing amount of domestic electricity (mainly from PV) that is used (and shifted by PHS). With CCGT imports, no imports are shifted by PHS, as the additional losses in PHS need to be offset by even more additional high-carbon imports.

3.2.2. H_2-FCEV

In Fig. 6 the H_2 supply for H_2-FCEV is displayed for all PV and import GHG scenarios along with corresponding losses in all conversion steps

[1] Scenario "LC import" and "13 TWh PV": Import direct use (=4.2 TWh) + Import via PHS (=1.1 TWh) / roundtrip efficiency PHS (=80%) = 5.6 TWh

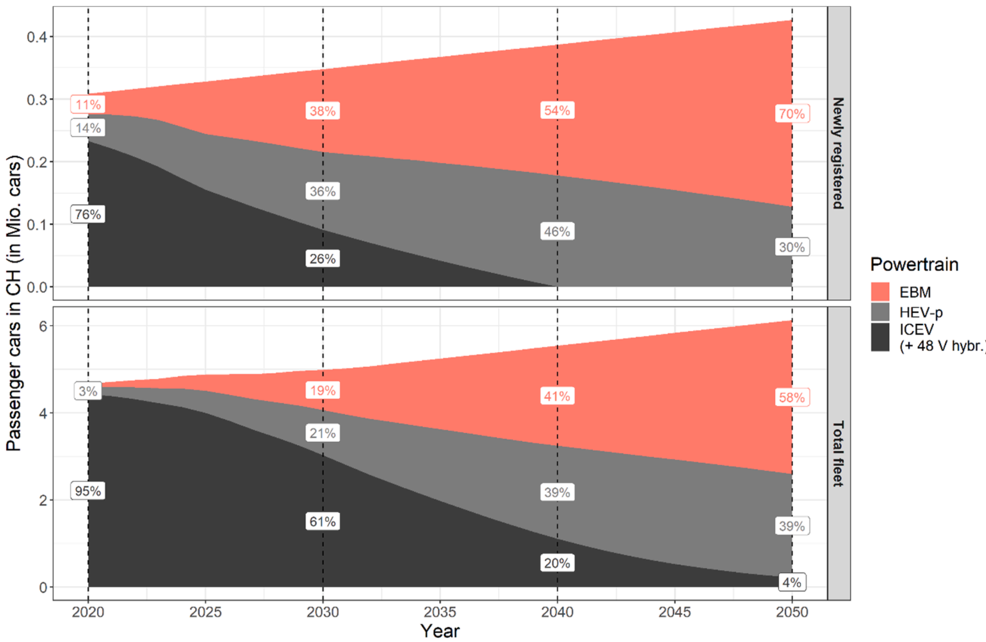

Fig. 4. Evolution of the fleet of newly registered (top) and total (bottom) Swiss passenger cars (areas) in order to comply with normative GHG emission targets. Labels show the percentage of each powertrain in the fleet. The penetration of EBM powertrains (BEV, H_2-FCEV and SNG-V) is the red area. In the reference scenario "non-EBM", this red area will remain fossil fuels-based with 60% gasoline and 40% diesel ICEV for all years until 2050. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Evolution of the annual end-energy demand of the EBM (BEV, H_2-FCEV, SNG-V) and the "non-EBM" (60% gasoline and 40% diesel) fleet from Fig. 4.

Powertrain	2020	2025	2030	2035	2040	2045	2050
	(in TWh_{fuel}/year)						
BEV	0.2	0.9	2.1	3.5	4.7	5.8	7
H2-FCEV	0.4	1.5	3.5	5.6	7.3	9.2	11
SNG-V	0.7	2.8	6.4	9.8	12	15	18.1
non-EBM	0.6	2.3	5.3	8.3	10.3	12.9	15.6

ELYSE, METH and SMR. H_2 is primarily produced from electricity and grid NG via ELYSE and SMR, respectively.

Grid NG is only used, if import electricity has a high-carbon footprint ("CCGT") and PV expansion in CH is low (13 TWh), since in this case, H_2 from grid NG via SMR features less GHG emissions than H_2 produced from non-renewable electricity. In all other cases, H_2 is primarily produced from electricity via ELYSE and directly used thereafter. With increased PV expansion in CH also the route of seasonal storage of H_2 as SNG is used more often, despite the additional losses of the two additional conversion steps (METH and SMR).

In Fig. 7, the origin of electricity used for ELYSE divided by imports and domestic (excess) electricity is shown along with the amount of electricity shifted by PHS. Import electricity is primarily used for ELYSE in the "LC" scenario with a low PV expansion in CH. In this case, no seasonal storage of H_2 as SNG is employed (see Fig. 6) as throughout the year (i.e. also in winter) enough low-carbon import electricity is available. The more PV is installed in CH - or if only high-carbon ("CCGT") imports are available - the more domestic excess electricity from PV in summer is used. In these cases, in summer, H_2 is produced by ELYSE in excess (i.e. more than can within short terms be used by H_2-FCEV), and then converted further to SNG (via METH) to be seasonally stored in the NG grid. In winter, when there is a lack of renewable electricity, the seasonally stored SNG is reconverted to H_2 via SMR. Short-term electricity storage via PHS is used - to a lower extent - with import electricity in the "LC'' scenario with 13 TWh PV and 32 TWh PV.

Depending on the PV expansion and import GHG scenario, the total amount of electricity needed to fuel H_2-FCEV in 2050 via ELYSE varies between 2.6 TWh (13 TWh PV; CCGT import) and 21.1 TWh (52 TWh PV; LC and CCGT import). These 2.6 TWh and 21.1 TWh correspond to about 5% and 35% of the current Swiss end-use electricity demand of about 57 TWh, respectively [77].

3.2.3. SNG-V

Fig. 8 depicts the SNG supply for SNG-V for all PV and import GHG scenarios along with corresponding losses in the ELYSE-METH step. No losses are assumed, if grid NG is directly used. Grid NG is primarily used, if import electricity has a high-carbon intensity (CCGT) and PV expansion in CH is low (13 TWh), as in this case, grid NG features less GHG emissions than SNG produced from (non-renewable) electricity. This is in particular the case with a large content of biomethane in the NG grid. Only in the scenario with a high PV expansion in CH (52 TWh) and LC imports, SNG is exclusively produced from 18.1 TWh electricity.

In Fig. 9, the origin of the electricity used for ELYSE-METH divided by import and domestic (excess) electricity is shown. Import electricity is - as in other EBM scenarios - primarily used in the "LC" import scenario with a low PV expansion in CH. The more PV is installed in CH, the more domestic excess electricity, which mainly occurs in summer, is used. With high-carbon ("CCGT") imports, grid NG rather than import electricity is used along with gradually more domestic excess electricity as PV expansion increases. In these cases, in summer, SNG is produced in excess and seasonally stored in the NG grid. In winter, when there is a lack of (renewable) electricity, the seasonally stored SNG is used again to meet the SNG-V demand. Short-term electricity storage via PHS is used - to a lower extent - with import electricity in the "LC'' scenario and decreasing PV expansion.

Depending on the PV and import GHG scenario, the total amount of electricity needed to fuel SNG-V in 2050 varies between 2.6 TWh (13 TWh PV; CCGT import) and 36.8 TWh (52 TWh PV; LC import). These 2.6 TWh and 36.8 TWh correspond to about 5% and 65% of the current Swiss end-use electricity demand of about 57 TWh, respectively [77].

3.3. Impact on the electricity system

3.3.1. Imported electricity

In Fig. 10, the totally required import electricity is shown for all PV expansion, import GHG and EBM scenarios (including "non-EBM" as dark-shaded bars and numbers below the bars). The additional import electricity demand of EBM compared to "non-EBM", as provided in the previous section, is annotated on top of the bars. Already in the "non-

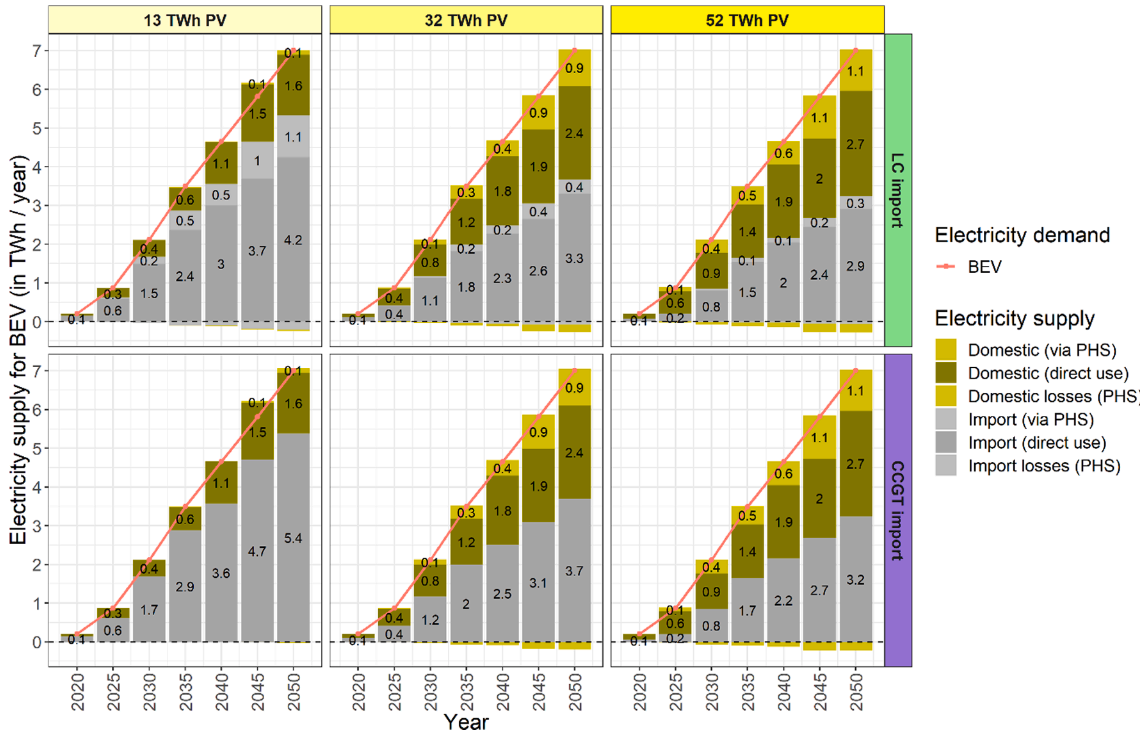

Fig. 5. Origins of electricity (import and domestic) to meet the end-energy (electricity) demand of BEV (red line) in all PV expansion and import GHG scenarios. Additionally, the share of electricity shifted by PHS and associated losses (negative values) are displayed. For comparison, the current Swiss end-use electricity demand is about 57 TWh [77]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

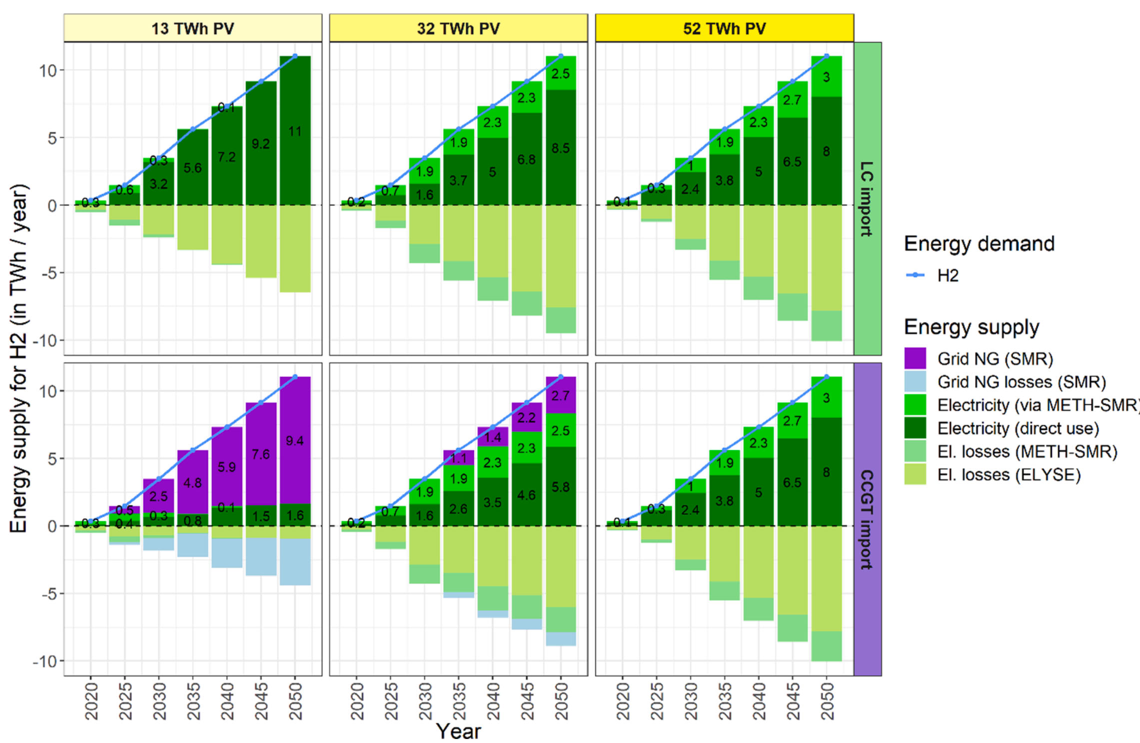

Fig. 6. Supply routes of H_2 (i.e. direct use from ELYSE, seasonal storage via METH-SMR and use of grid NG via SMR) to meet the end-energy (H_2) demand of H_2-FCEV (blue line) in all PV expansion and import GHG scenarios. Additionally, associated losses (negative values) within the conversion steps ELYSE, METH and SMR are displayed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

EBM" scenario a substantial amount of electricity must be imported. Depending on the year and PV expansion, this amount is between 1 TWh (in 2020 and 2025 with the highest PV expansion scenario) and 14 TWh (in 2040 with the 13 TWh PV expansion and LC imports).

In 2050, compared to "non-EBM" and depending on the PV and import GHG scenario, BEV need between +3 and +6 TWh, H_2-FCEV

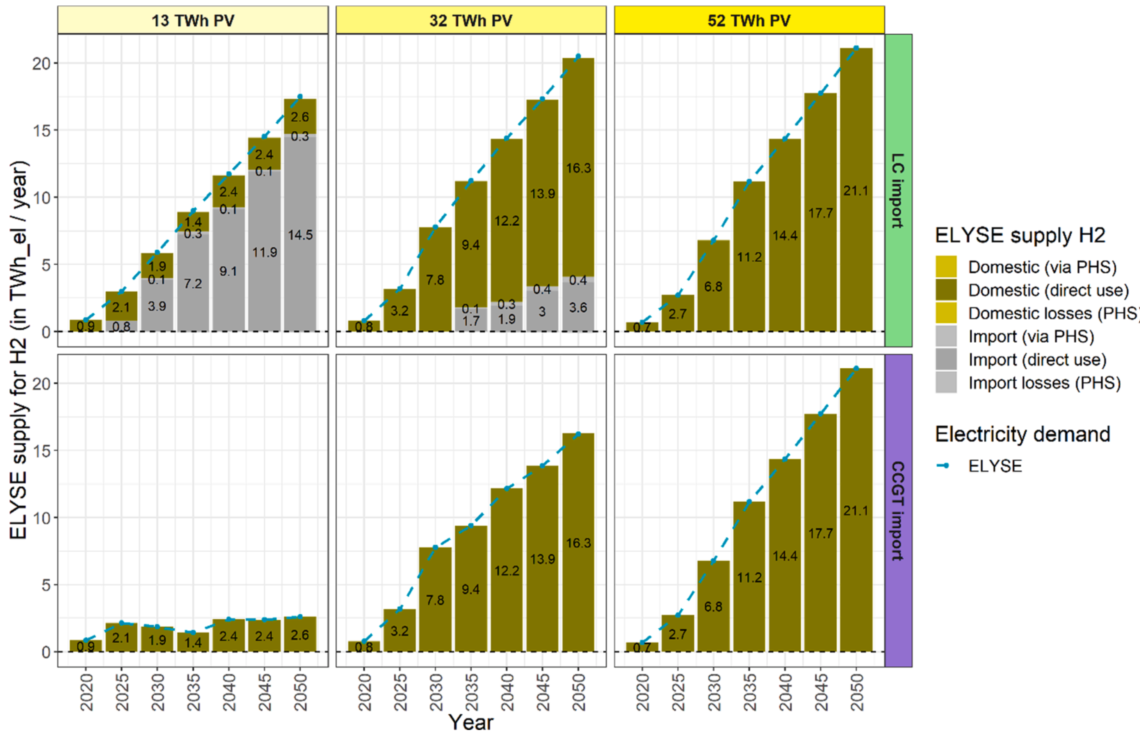

Fig. 7. Origin of electricity (import and domestic) used in the ELYSE step to produce H_2 for H_2-FCEV. Additionally the share of electricity shifted by PHS and associated losses are displayed. NOTE: The energy equivalent of grid NG used to supply H_2-FCEV (via SMR) is not shown. For comparison, the current Swiss end-use electricity demand is about 57 TWh [77].

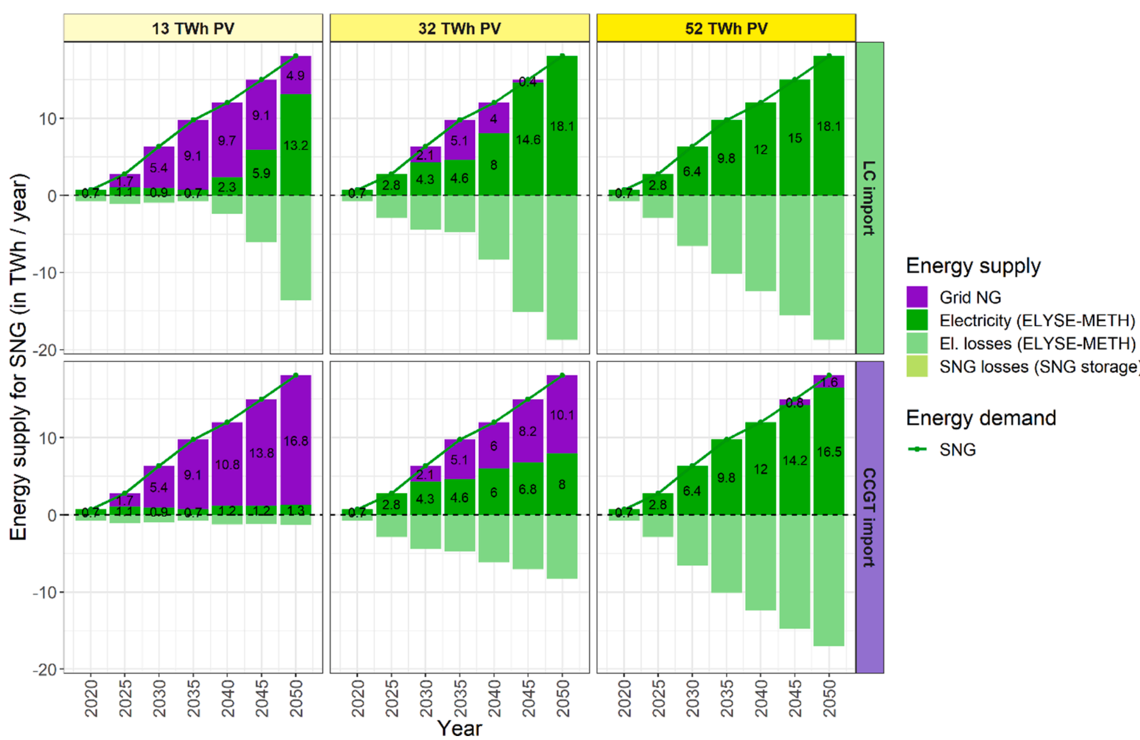

Fig. 8. Supply routes of SNG (i.e. from electricity via ELYSE-METH and direct use of grid NG) to meet the end-energy (SNG) demand of SNG-V (green line) in all PV expansion and import GHG scenarios. Additionally, associated losses (negative values) within the conversion step ELYSE-METH are displayed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

between +0 and +15 TWh and SNG-V between +0 and +25 TWh of additional import electricity. While BEV need additional import electricity in both import GHG scenarios because of a lack of seasonal storage options, H_2-FCEV and SNG-V only need additional import electricity in the "LC" scenario, as in the "CCGT" scenario they can use PV excess electricity via seasonal storage and/or grid NG (see above). For

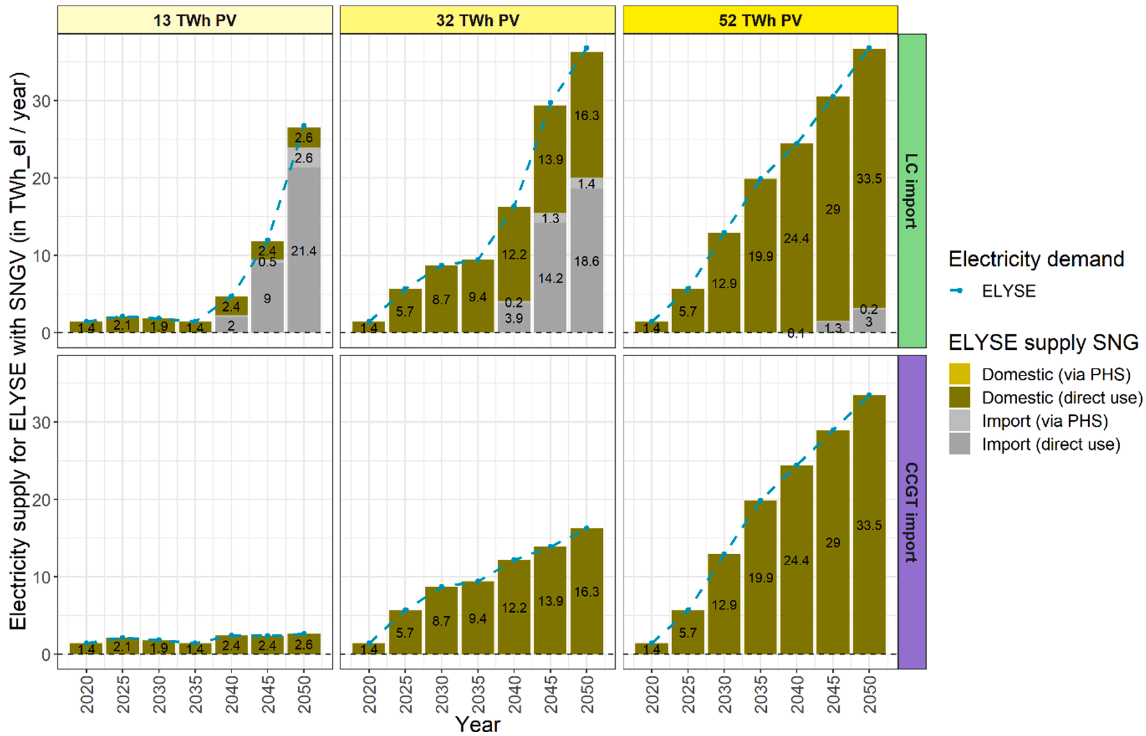

Fig. 9. Origin of electricity (import and domestic) used in the ELYSE-METH steps to produce SNG for SNG-V. Additionally the share of electricity shifted by PHS and associated losses are displayed. NOTE: The energy equivalent of grid NG used to supply SNG-V is not shown. For comparison, the current Swiss end-use electricity demand is about 57 TWh [77].

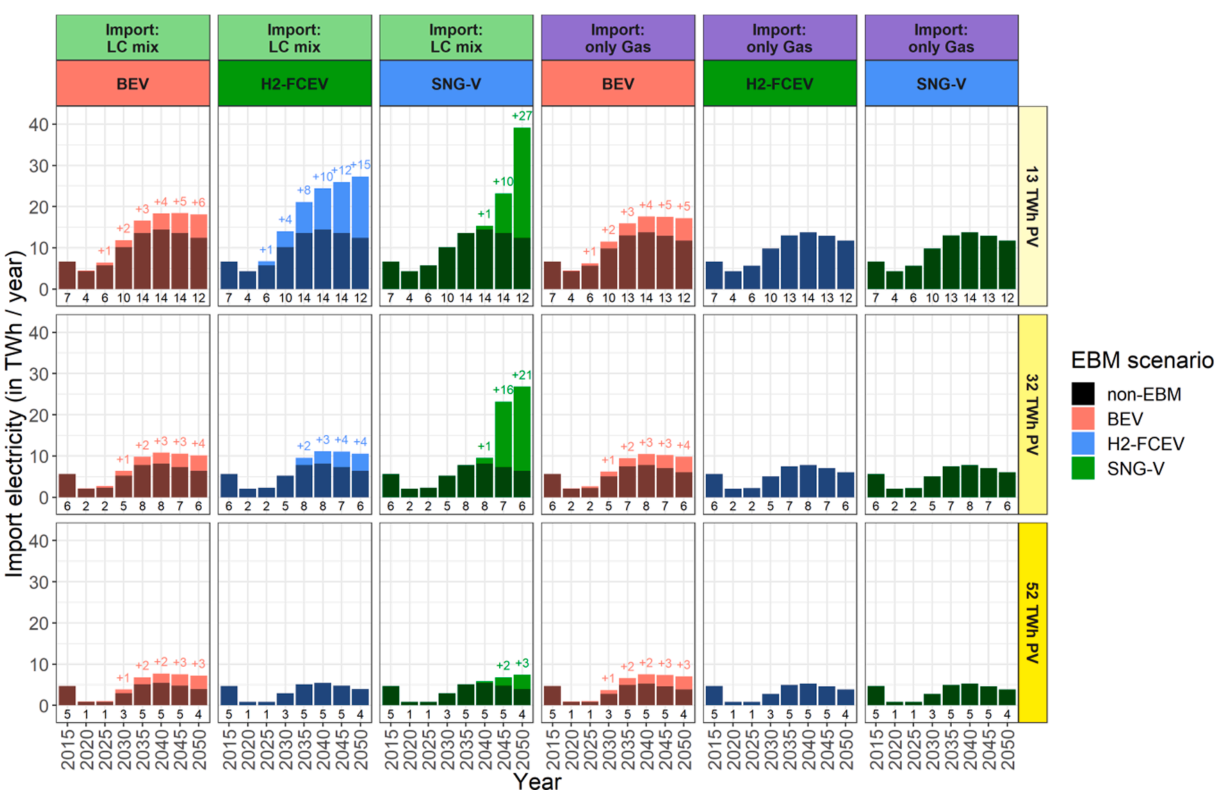

Fig. 10. Required import electricity for the different EBM, PV and import GHG scenarios. As a comparison also the required import electricity in the "non-EBM" scenario is displayed as overlapping black-shaded bars and numbers below the bars. The additional import electricity compared to "non-EBM" is shown as numbers above the bars. For comparison, the current Swiss net imported electricity amount in the winter half year is between 4 and 7 TWh [78].

comparison, the current Swiss net imported electricity amount in the winter half year is between 4 and 7 TWh [78].

3.3.2. Excess electricity

Fig. 11 displays the annual excess electricity in all PV expansion, import GHG and EBM scenarios (including “non-EBM” as black-shaded bars and numbers below the bars). For comparison, also the total Swiss PV production in each year and scenario is displayed. This excess electricity can be converted to other energy carriers (e.g. SNG via power-to-X) or must be curtailed. Depending on the PV expansion scenario, with “non-EBM”, excess electricity amounts to less than 3 TWh in the lowest PV scenario (13 TWh PV) and more than 34 TWh in the highest PV scenario (52 TWh PV) by 2050. In other words, in several “non-EBM” and “BEV” scenarios a large PV expansion results in more than 50% of the PV generation becoming excess electricity. Depending on the EBM scenario, this excess electricity can be reduced substantially with H_2-FCEV and SNG-V due to their capability of seasonally storing it as SNG. With BEV, due their overall lower fuel demand and no seasonal fuel storage, a large amount of this excess electricity remains in the energy system. In other words, in the BEV (and non-EBM) scenario with a high PV expansion more than half of the annually produced PV electricity (yellow line in Fig. 11) is excess electricity.

In order to put these amounts of excess electricity into context with energy demands in other sectors, heavy-duty (HD) vehicles (i.e. vans, trucks, cargo trains, etc.) currently consume about 12 TWh of fossil energy (mainly diesel) [79]. With state-of-the-art TTW efficiencies and the conversion losses of ELYSE-METH in this study, this would result in an equivalent electricity demand of about 17 TWh and 29 TWh for HD-H_2-FCEV and HD-SNG-V, respectively. Electric HD vehicles are not considered because of the (still) high energy requirements and low energy density of batteries [80]. Fig. 11 shows that in all PV expansion scenarios with BEV, there would be enough excess electricity to (at least partially) fuel such HD vehicles. However, this would mean that in addition to an infrastructure for BEV (e.g. charging stations, grid reinforcements, etc.) also a power-to-X infrastructure with ELYSE (and METH) must be installed. The required ELYSE capacities in 2050 would range between 7 GW_{el} and 35 GW_{el} in the 13 TWh and 52 TWh PV scenario, respectively, while corresponding equivalent full-load hours (eqFLH) are typically below 2000 h. In order to be economically viable, eqFLH of ELYSE should be at least 4000 h [28]. For more information on these required ELYSE capacities and eqFLH as well as on how to increase them, refer to section S.10 in the supplementary materials. Advanced economical and technical aspects of such ELYSE operation as well as the build-up of parallel infrastructure for both BEV and additional SNG production for HD transportation are out of the scope of this study.

3.3.3. Short-term electricity storage

Fig. 12 shows how short-term electricity storage (i.e. PHS) is used in all scenarios and years in comparison to the “non-EBM” scenario. With BEV, compared to “non-EBM”, substantially more electricity (mainly from PV) is stored in PHS, in particular with “LC” imports and large PV expansions to shift renewable electricity from noon (supply peak) to evening/night hours (demand peak). With plenty of renewable electricity available in the system at noon (either from domestic or abroad supply), this day-night shift is more GHG-efficient than importing (high-carbon) electricity at night despite the additional losses incurred by the “round-trip-efficiency” of PHS (80%). An improvement of this situation could only be achieved by demand response (i.e. increased «noon charging» of BEV).

With H_2-FCEV and SNG-V, a reduction in the use of PHS - compared to “non-EBM” - is observed with “LC” imports and for all PV expansion scenarios in almost all years. This is due to the fact that in these cases, low-carbon electricity can at almost any time directly be converted to H_2 and afterwards be stored as H_2 (or SNG) more efficiently than in PHS. With H_2-FCEV and SNG-V as well as high-carbon (“CCGT”) imports, PHS is used almost as in “non-EBM”, since in this case H_2 and SNG are primarily produced from grid NG (see Figs. 6 and 9).

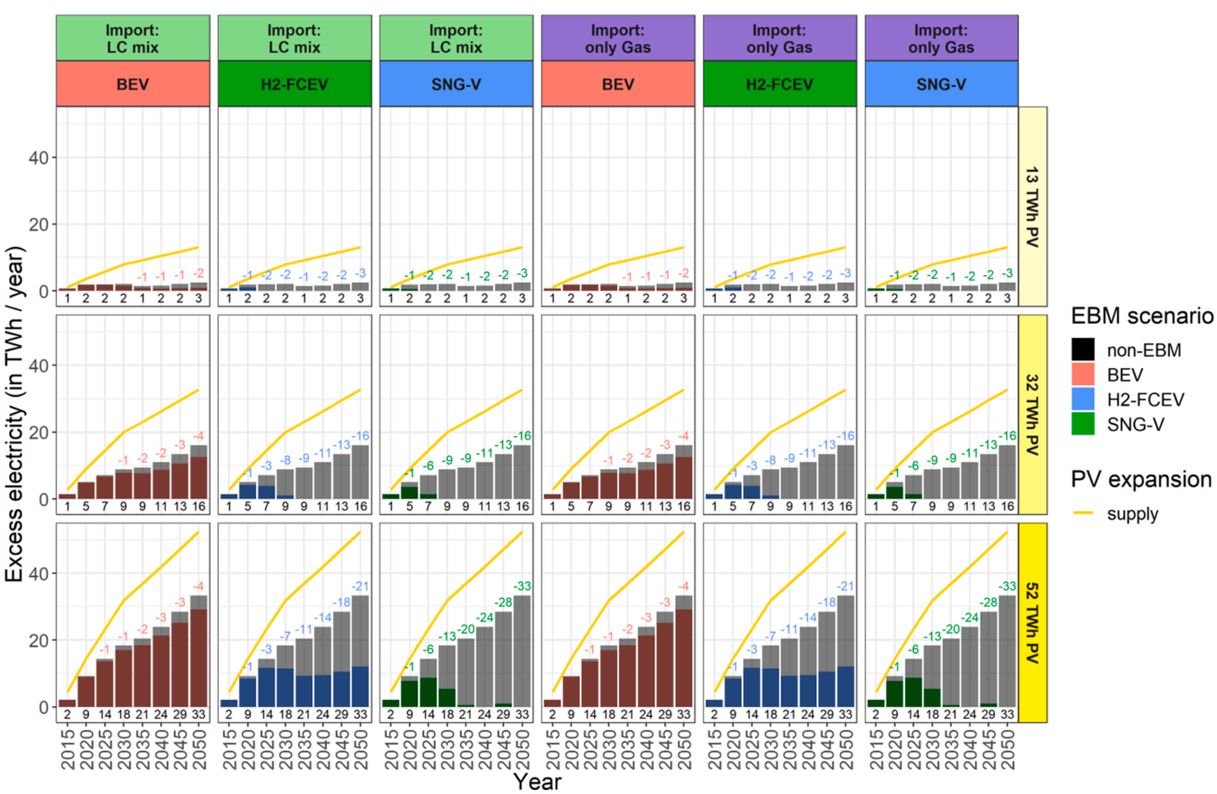

Fig. 11. Annual excess electricity (bars) and annual PV production (yellow line) for all EBM, PV and import GHG scenarios (see Fig. 10 for more details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

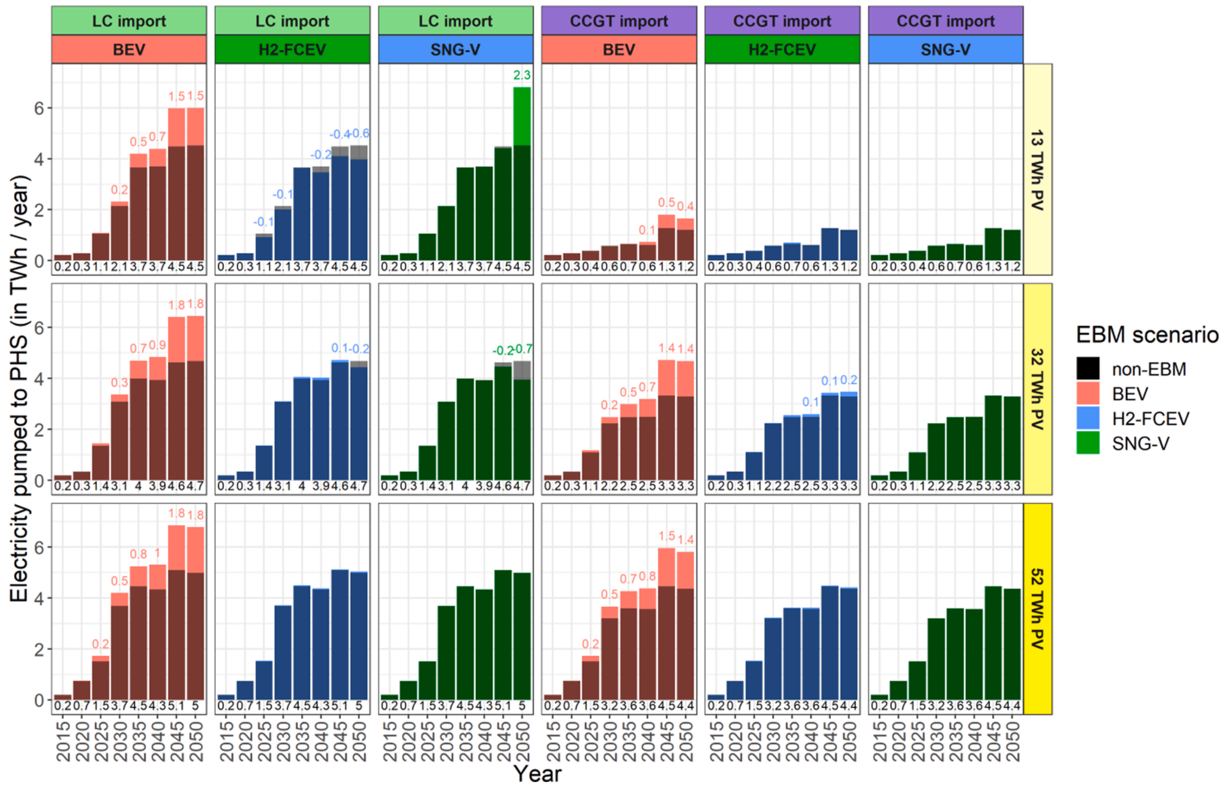

Fig. 12. Amount of electricity stored with PHS for the different EBM, PV and import GHG scenarios (see Fig. 10 for more details).

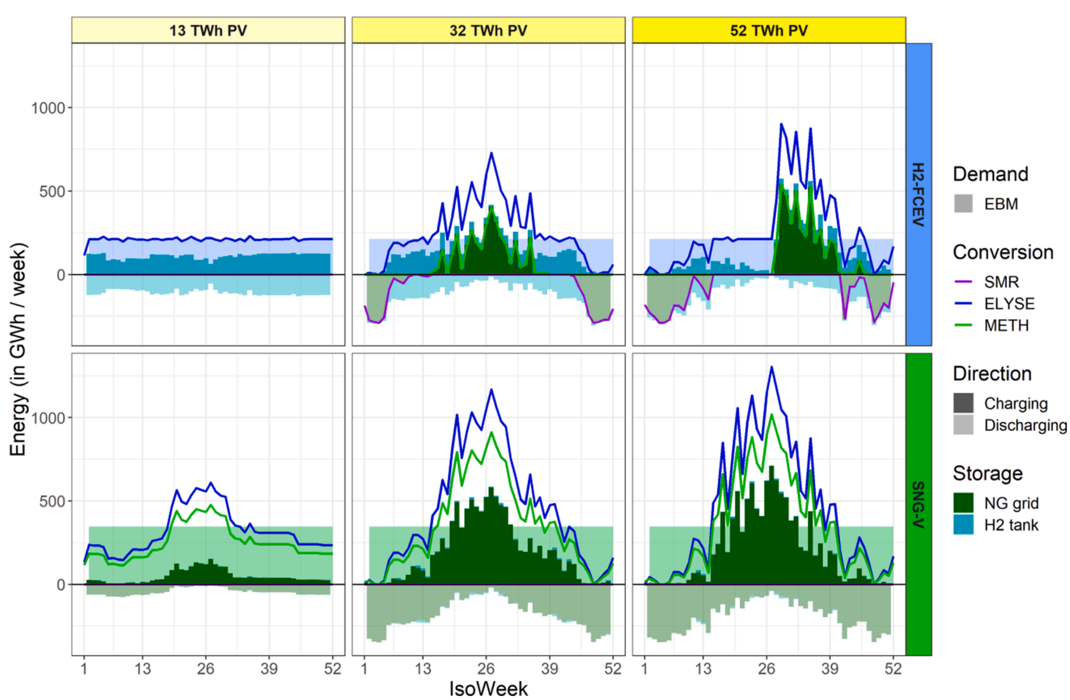

Fig. 13. Weekly aggregated seasonal (NG grid) and short-term (H_2 tank) storage with H_2-FCEV and SNG-V for the exemplary year 2050 for all PV expansion scenarios and the "LC" import GHG scenario. Storage "charging" is displayed as positive values and "discharging" as negative values. As shaded areas also the weekly end-energy demand of H_2-FCEV and SNG-V is shown. The weekly operation of ELYSE, METH and SMR is shown as solid lines.

3.3.4. Seasonal and short-term H_2 and SNG storage

Fig. 13 shows at a weekly aggregated time resolution for the exemplary year 2050, how much H_2 and SNG is weekly charged and discharged in the generic H_2 storage tank (short-term H_2 storage) and NG grid (seasonal SNG storage) as well as how much is converted by ELYSE, METH and SMR to produce H_2 and SNG in all PV expansion scenarios with "LC" imports. Only the "LC" import scenario is shown, as in the "CCGT" scenario, H_2 and SNG are primarily produced from grid NG, as this is more GHG efficient. Similar, albeit smaller, effects can also be observed in the "CCGT" scenario, however. For more information on this seasonal and short-term H_2 and SNG storage, refer to section S.8 in the supplementary materials.

3.4. GHG emissions

3.4.1. GHG intensity of imported and domestically produced electricity

Fig. 14 shows the evolution of the CH– and EU-wide electricity generation mix from 2015 to 2050 for the "LC" scenario obtained from EUSTEM. Nuclear power is phased out by 2035 in CH, while a substantial expansion of PV and wind occurs. This PV expansion in Switzerland represents the "13 TWh PV" scenario in this study. In the EU, nuclear and fossil generation (coal and gas) are also phased out or replaced with CCS technologies and a substantial increase in wind, PV, and other renewable technologies.

The hourly GHG intensity of imported ("LC" or "CCGT") and domestically produced ("CH") electricity is displayed in Fig. 15 for a typical day in each season and all years. A distinction between weekends and weekdays is not made. For domestic production, a distinction between the 13 TWh and 52 TWh PV scenarios is made. Due to the increasing share of renewables (mostly PV and wind) and CCS in the "LC" scenario, the gap between the GHG intensity of "LC" and "CCGT" import electricity increases with every year. In the "CCGT" scenario, the GHG intensity is constant during a specific year, but drops from 423 g CO_2-eq / kWh in 2015 to 360 g CO_2-eq / kWh in 2050. In the "LC" scenario, there is a clear seasonal and diurnal variability of the GHG intensity. Regarding the seasonal variability, GHG intensities are highest in winter and lowest in summer. Regarding the diurnal variability, in all seasons, the GHG intensity drops at noon due to increased PV supply and increases at night due to more conventional-thermal generation. This nightly increase, however, decreases with larger shares of wind generation, which typically produces low-carbon electricity at night and in winter. This way, the annual average GHG intensity of imported electricity in "LC" decreases from 319 g CO_2-eq / kWh in 2015 to 73 g CO_2-eq / kWh in 2050. Due to the large share of low-carbon electricity generation technologies, the average GHG intensity of the domestic ("CH") supply mix is low between 12 and 21 g CO_2-eq / kWh throughout all years, seasons and PV expansion scenarios. The highest diurnal GHG intensities in "CH" occur at noon due to an increased contribution of domestic PV generation with a relatively higher GHG intensity compared to nuclear and hydro power (see Table S-2 in supplementary materials).

3.4.2. Systemic GHG emissions

Fig. 16 shows the overall (systemic) GHG emissions (including all life-cycle GHG emissions) associated with the three EBM (BEV, H_2-FCEV, SNG-V) and "non-EBM" powertrains for the three PV expansion and two import GHG scenarios ("LC" / "CCGT") for all years 2015 to 2050. A distinction between "additional SNG production" (three left columns) and "curtailment" (three right columns) of excess electricity is made (see Section 2.3.9). Arrows indicate the additional GHG emissions of the EBM fleet added on top of the GHG emissions tied to the base electricity demand (dark grey area). GHG savings of the EBM against the reference "non-EBM" fleet are displayed as a light grey area along with their absolute numbers in 2050. GHG savings due to sector coupling ("add. SNG prod.") are displayed as a negative light blue area.

Irrespective of the PV expansion and import GHG scenario, all EBM powertrains always feature substantially lower GHG emissions than a corresponding "non-EBM" fleet. Systemic GHG savings of EBM compared to non-EBM range between −1.7 (−15%) Mt CO2-eq ("SNG-V"; "13 TWh PV"; "CCGT"; "add. SNG prod.") and −4.3 (−49%) Mt CO2-eq ("SNG-V; 52 TWh PV; LC; "curtailment") by 2050.

Regarding the three EBM powertrains individually, a clear distinction must be made between the scenarios and in particular with regard to excess electricity:

- **"Add. SNG prod.":** If additional SNG production from "excess" electricity due to a large PV expansion in Switzerland is possible and no curtailment occurs because there is enough additional demand for this SNG (e.g. heavy-duty transportation, process heat, etc.), BEV is in all scenarios the most GHG-efficient powertrain. The annual GHG reduction in 2050 with BEV compared to "non-EBM" in this case varies between −2.1 (−19%) Mt CO2-eq ("BEV"; "13 TWh PV"; "CCGT"'; "add. SNG prod.") and −3.7 (−45%) Mt CO2-eq ("BEV", "13 TWh PV", "LC"; "add. SNG prod."). Within one GHG import

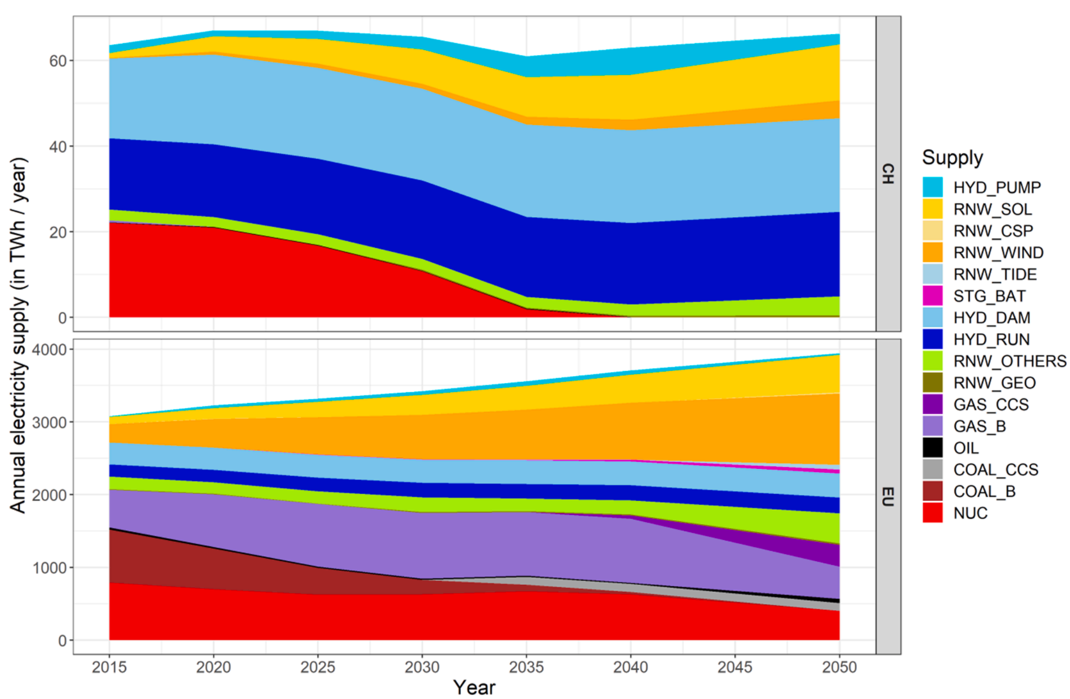

Fig. 14. Evolution of the annual Swiss (CH) and European (EU) electricity supply mix from 2015 to 2050 based on the low-carbon (LC) scenario in the EUSTEM optimization model (abbreviations are explained in "nomenclatures"). The PV expansion in CH represents the "13 TWh PV" scenario in this study.

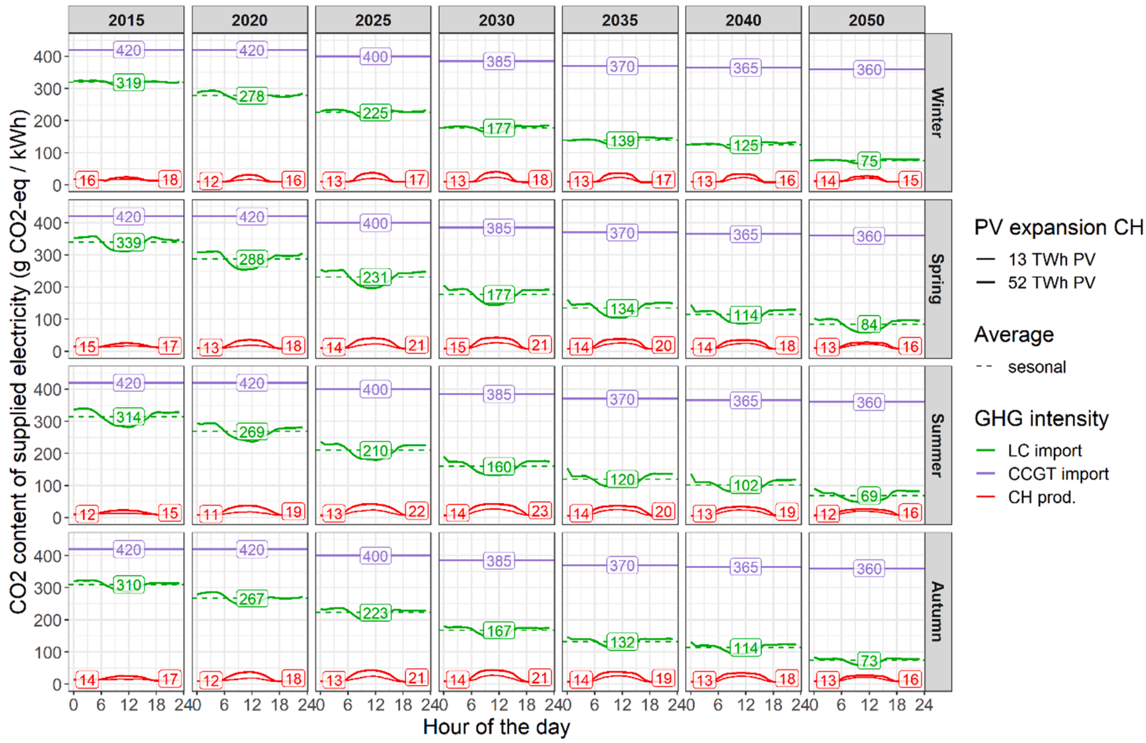

Fig. 15. Hourly GHG intensity of imported ("LC" and "CCGT" scenario) as well as domestically produced ("CH") electricity divided by seasons and years. Seasonal averages are given in labels. For "CH" production, a distinction between the two PV expansion scenarios (13 and 52 TWh PV) is made.

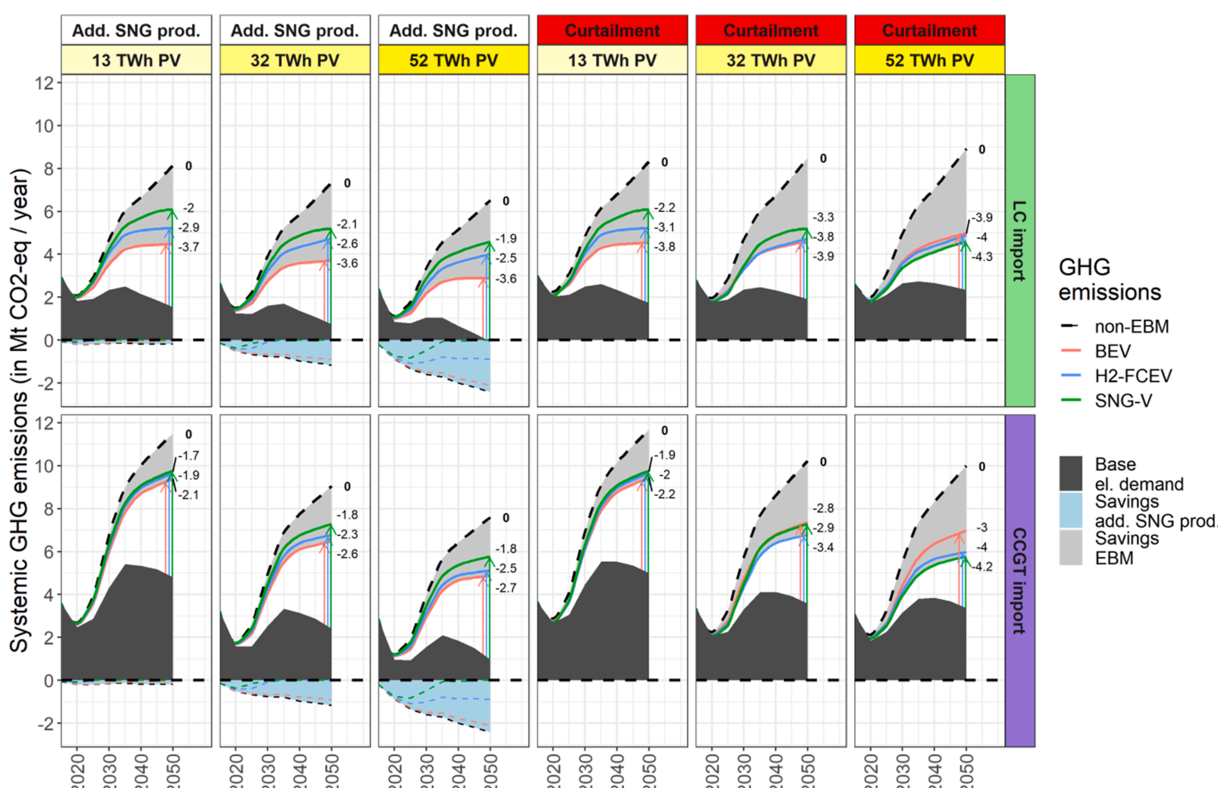

Fig. 16. Overall (systemic) GHG emissions (in Mt CO_2-eq / year) for all EBM (BEV, H_2-FCEV, SNG-V) and "non-EBM" scenarios in all PV expansion and import GHG scenarios. A distinction between "additional SNG production" and "curtailment" of excess electricity is made. The dark grey area shows the GHG emissions of the base electricity demand in the electricity sector (without mobility). The light grey area shows GHG savings of EBM powertrains against the "non-EBM" fleet. GHG savings due to "Add. SNG prod." are displayed as a negative light blue area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

scenario (“LC” or “CCGT”), GHG savings increase with an increasing PV expansion, in particular with CCGT imports. Without curtailment, also SNG-V and H_2-FCEV save at least −1.7 (−15%) Mt CO2 (“SNG-V”; “13 TWh PV”; “CCGT”; “add. SNG prod.”) against a corresponding "non-EBM" fleet.

- **“Curtailment”:** If there is substantial curtailment of excess electricity, H_2-FCEV and - with even more PV - SNG-V become equally or more GHG-efficient than BEV. This is in particular the case when considering high-carbon CCGT imports, where already in the 32 TWh PV case, scenarios with H_2-FCEV and SNG-V are slightly more GHG-efficient than BEV. This is mainly due to the fact that H_2-FCEV and SNG-V can either directly use the available excess electricity via ELYSE-METH or seasonally store it for times with otherwise only high-carbon electricity. Moreover, H_2-FCEV and SNG-V have the option to temporarily use grid NG, if electricity features higher GHG emissions. This increased flexibility in fuel supply and seasonal storability are assets of H_2-FCEV and SNG-V that BEV do not have and that result in equal to even lower systemic GHG emissions despite additional conversion losses and lower TTW powertrain efficiencies. Differences in terms of GHG mitigation between the three EBM technologies - given a scenario - are, however, typically small (i. e. less than 1 Mt CO2-eq by 2050). Therefore, with curtailment, only the extreme scenarios, namely “13 TWh PV” and “LC’’ as well as “52 TWh PV” and “CCGT”, show a clear superiority of particular EBM powertrains over the other(s), namely, BEV and SNG-V (and H_2-FCEV), respectively.

The two cases regarding the utilization of excess electricity can be seen as the two extremes with respect to systemic GHG emissions. These findings furthermore highlight the importance of using all excess electricity to reduce the allocated GHG impacts to BEV. In other words, a large BEV expansion in an energy system with large shares of PV is only more sustainable than other EBM powertrains, namely H_2-FCEV and SNG-V, if sector coupling (power-to-X) is established alongside and if there are other energy sectors that can use this energy.

3.4.3. Specific GHG emissions

Specific GHG emissions of each powertrain are the difference between the GHG emissions tied to the base electricity demand (dark grey area) and the total systemic GHG emissions (lines) in Fig. 16. In 2050, for all EBM powertrains, they are indicated by arrows and can also be interpreted as short-term marginal GHG emissions. Given the total mileage of each powertrain, the specific GHG emissions of each powertrain per km travelled are obtained. This is shown in Fig. 17 for all scenarios as well as a distinction between “Add. SNG prod.” and “Curtailment” of excess electricity (as in Fig. 16). This representation of GHG emissions associated with each powertrains allows for more straightforward and more understandable comparison also with regard to legislative GHG emission targets in mobility.

Depending on the year, PV expansion and import GHG scenario, these specific GHG emission range between 160 g CO_2-eq / km and 74 g CO_2-eq / km for BEV, 187 g CO_2-eq / km and 71 g CO_2-eq / km for H_2-FCEV and 215 g CO_2-eq / km and 62 g CO_2-eq / km for SNG-V, which is notably the lowest specific GHG emissions achieved by all EBM powertrains in the considered scenarios.

3.5. Applied value for policy and decision makers

Results from this study provide applied value to energy policy and decision makers: It shows that significant GHG emission reductions are possible by introducing electricity-based mobility (EBM) with BEV, H_2-FCEV and/or SNG-V powertrains. Due to the fluctuating and seasonal unbalanced availability of renewable electricity, the comparison of these three EBM powertrains is, however, complex. Therefore, in order to most effectively decarbonize the energy system, all its aspects and boundary conditions should be considered when comparing different technologies. Such an integral assessment of powertrain technologies should in particular take into account the full temporal dynamics of the

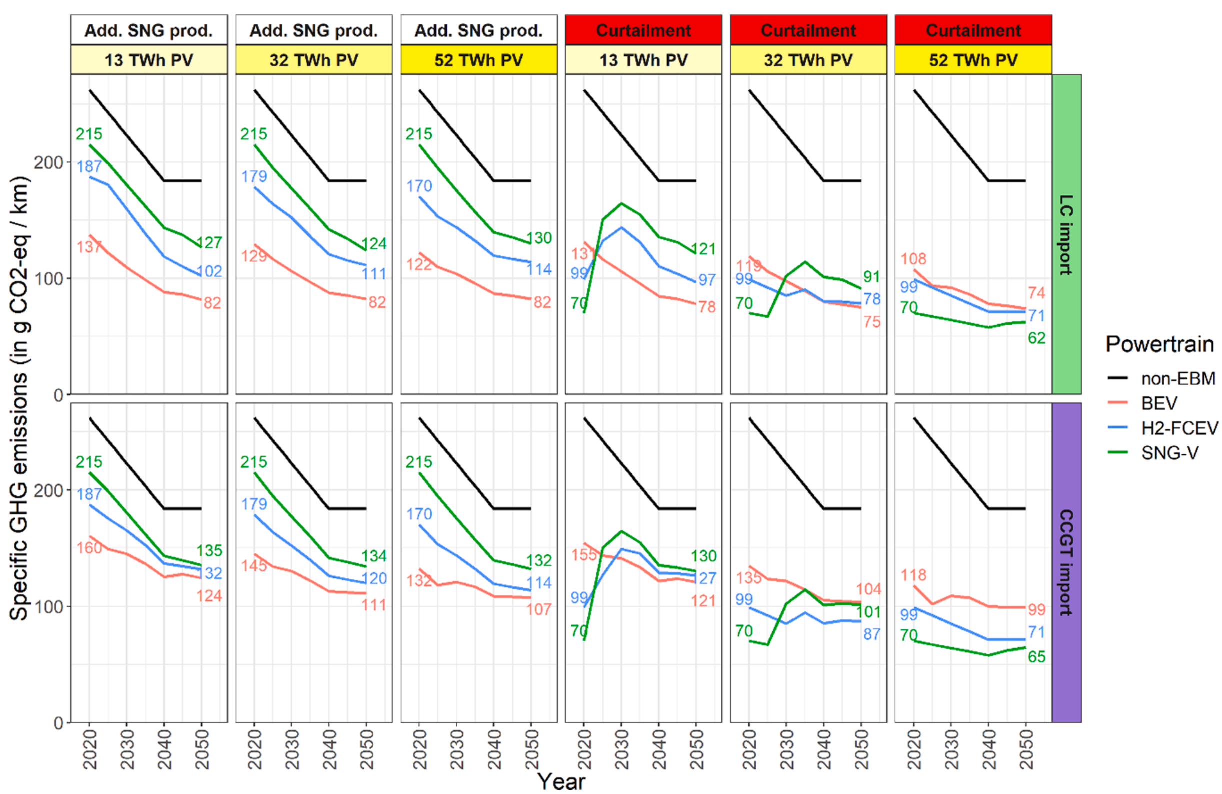

Fig. 17. Specific life-cycle GHG emissions (in g CO_2-eq / km travelled) for all EBM (BEV, H_2-FCEV, SNG-V) and “non-EBM” powertrain scenarios in all PV expansion and import GHG scenarios. A distinction between “additional SNG production” and “curtailment” of excess electricity is made.

energy system including all relevant sectors and interconnections.

The authors therefore recommend policy and decision makers to promote a rapid phase-out of fossil fuels for mobility and to establish more market and technology development for EBM powertrains. Due to the additional electricity demand of EBM, the authors further recommend to increase renewable electricity installation (e.g. PV) and to invest in curtailment-avoidance measures such as demand side management, short- (e.g. batteries, etc.) and long-term (e.g. H_2 or SNG) energy storage as well as sector coupling (power-to-X). Because high-carbon electricity limits the GHG mitigation potential of EBM, concepts to increase the availability of low-carbon energy during electricity shortages (e.g. in winter) should be developed (e.g. seasonal energy storage, import of renewable chemical energy carriers, etc.).

3.6. Limitations and further research

The study does not cover energy demands outside the electricity and passenger cars mobility sectors, such as heating, industry and/or heavy-duty transportation. These sectors may also have a potential to use excess electricity and avoid curtailment. In turn, especially space heating is supposed to increase electricity demand and hence, potentially electricity imports required in winter, which could have an impact on the imported electricity mix. For further study, also other energy sectors and their impacts on GHG emissions should be assessed in a quantitative manner and from a technological point of view. Moreover, socio-economic aspects could be included to allow for a sustainable long-term market penetration of EBM. For instance, efficiency gains may be offset by a growing need for heavier and more powerful vehicles as well as growing distances travelled.

For EBM vehicles, average mileages are assumed. In reality, they differ quite strongly depending on vehicle categories and use patterns. If mainly low or high mileage vehicles became EBM, this would have an impact on GHG emissions. Other aspects to consider are investment and operational costs in general, driving range and on-board fuel storage, availability and performance of charging infrastructure (e.g. fast-charging).

It is assumed that all excess electricity can be converted to H_2 and SNG. However, in order to be economically viable, a certain equivalent full load hour requirement of H2 and SNG production plants must be reached, therefore, the actual H_2 and SNG production may be overestimated. This can be improved by taking into account techno-economic boundary conditions of H_2 and SNG production.

No renewable (synthetic) gasoline or diesel is assumed to be used with non-EBM vehicles. Such synfuels could reduce the difference in the achieved GHG mitigation between EBM and non-EBM scenarios and could therefore also be considered in further study.

Fixed battery charging profiles without flexibility in terms of demand of BEV charging are used. Such flexibility options may further reduce GHG emissions of BEV. With regards to demand side management, flexible BEV charging and vehicles-to-grid (V2G) should be considered.

No “mixed fleet” of different EBM powertrains in the same energy system is considered. Such “mixed fleets” could however provide synergetic effects which may further reduce GHG emissions in the energy system.

Only GHG emission are considered as environmental impacts of EBM. For further study, an integral evaluation of the overall environmental performance of EBM with regard to local emissions, metal depletion, etc. is worthwhile.

4. Conclusions

In this study, the impacts of electricity-based mobility (EBM) powertrains (battery electric vehicles BEV, H_2 fuel cell electric vehicles FCEV and synthetic natural gas vehicles SNG-V) are investigated with respect to systemic life-cycle greenhouse gas (GHG) emissions compared to a corresponding reference “non-EBM” (60% gasoline and 40% diesel) passenger cars fleet in Switzerland. To this end, the penetration of EBM powertrains and their end-energy demand have been modelled in a legislation compliant way along with the evolution of the Swiss and European electricity generation mix and associated GHG emissions. Systemic GHG emissions have been investigated with a supply chain model of EBM fuels within several scenarios regarding different domestic PV expansions, GHG intensities of imported electricity and the utilization of “excess” electricity (curtailment vs. sector coupling).

Depending on the scenarios, the following main conclusions can be drawn:

- **All scenarios:** In all scenarios, irrespective of the domestic PV expansion and GHG content of imported electricity, EBM generally features significantly lower GHG emissions than a corresponding “non-EBM” fleet.
- **Scenarios with “Sector coupling”:** If no electricity must be curtailed due to additional flexibility options such as sector coupling, demand side management and/or seasonal storage, BEV generally feature the lowest systemic GHG emissions of all EBM powertrains.
- **Scenarios with “Curtailment”:** In turn, if a large part of electricity must be curtailed, BEV are only substantially more GHG-efficient in an energy system with low to medium domestic PV expansion and low-carbon electricity imports. In several scenarios with curtailment, H_2-FCEV and SNG-V (with CO_2 supplied via direct air capture) are at least equally GHG-efficient - or with a high PV expansion and high-carbon electricity imports - even more GHG-efficient than BEV. This is due to the fact the H_2-FCEV and SNG-V, despite their lower tank-to-wheel efficiency and additional losses in the conversion steps of electrolysis and methanation, feature a longer (seasonal) storability of their fuels (e.g. as SNG in the natural gas grid) and therefore they have a higher flexibility with regard to the GHG content of their used electricity. Moreover, they may resort to grid natural gas (for H_2-FCEV via steam methane reforming) at times when the GHG content of electricity is higher (including conversion losses) or resort to imported renewable SNG and H_2 from a global scale. This can increase opportunities in managing seasonal excess or shortage of electricity. This is in particular the case, if grid natural gas has a high share of biomethane or imported SNG. However, with moderate curtailment, generally differences in terms of GHG emissions between EBM powertrains are small, except for “extreme” cases regarding domestic PV expansion and GHG content of import electricity.

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CRediT authorship contribution statement

Martin Rüdisüli: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Christian Bach:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing. **Christian Bauer:** Formal analysis, Investigation, Methodology, Writing – original draft. **Didier Beloin-Saint-Pierre:** Formal analysis, Investigation, Validation, Writing – review & editing. **Urs Elber:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Gil Georges:** Resources, Investigation. **Robert Limpach:** Formal analysis, Software. **Giacomo Pareschi:** Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Ramachandran Kannan:** Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Sinan L. Teske:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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